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INFORMATION PROCESSING ORGANIZATIONS WITH ACYCLICAL INFORMATION STRUCTURES

Alexander H. Levis, M.M. Tomovic, and P.H. Cothier
Massachusetts Institute of Technology

for

Contracting Officer's Representative
George.H. Lawrence

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Information theory models were used to analyze the effects of different perceptions of uncertainty and the relative value of tasks held by individual decision makers on organizational performance. The definition and evaluation timeliness as a measure of the effectiveness of command and control systems was also examined.

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EXECUTIVE SUMMARY

The goal of the research was the development of a mathematical theory of task-oriented organizations, where the tasks are primarily information processing and decision making.

Information theoretic models were used to analyze the effect of different perceptions of uncertainty and relative value of tasks by individual decision makers on organizational performance. The definition and evaluation of timeliness as a measure of effectiveness of command and control systems was also addressed.

A measure of organizational effectiveness was developed for the case in which systems designer and decision maker differ in their perception of the uncertainty associated with inputs or tasks. This measure was defined as the ratio of strategies that yield satisficing performance to the total admissible strategies. A hierarchical and a parallel three-person organization were used to illustrate the results. The complexities of assessing the timeliness of C3 systems were addressed through the extension of the system effectiveness methodology to consider not only the structure and protocol of a C3 system, but also the effect of doctrine on measures of effectiveness. Again, the theoretical development were illustrated through application to a generic C^3 system.

The overall research effort will contribute to methodologies for the analysis, design, and evaluation of command and control systems that support tactical Army organizations.

1. INTRODUCTION

When information processing and decision making tasks, which have to be performed, exceed the capabilities of a single decision maker, organizations are formed. The functions that each organization member is allocated, the interactions among the members, and the protocols that govern these interactions constitute the organizational form or structure. This structure, in turn, affects the individual member's workload, as well as the performance of the organization as a whole.

The point of view taken in this report is that of the organization designer. Given a set of tasks, the designer develops an organizational structure and then evaluates it to determine if it meets a set of performance requirements. If it does, then the next step is to assess the sensitivity of the design to the assumptions. To carry out the assessments, it is necessary that a methodology be developed and that measures of effectiveness, appropriate for the problem at hand, be developed.

Both of these steps are addressed in this report. They are imbedded in a broader framework, that of the development of an analytical methodology for the design and evaluation of command and control organizations. Consequently, for completeness, elements of that methodology, which form the basis for the specific results obtained in this investigation, will be presented. First, in Chapter 2, the basic model of the interacting decisionmaker, developed by Boettcher and Levis [1], [2], [3] will be introduced and its properties described.

In the following chapter, the model of organizations performing demanding tasks under time contraints is presented and the methodology for evaluating them is given in some detail, since it is the focus of the research carried out under this contract. In developing a design, the designer assumes that he knows the uncertainty that characterizes the tasks to be performed by the organization and that he also knows the value of each task. He also assumes that the organization members, in processing the information and making decisions, have identical knowledge of task uncertainty and perception of task value. In general, it is very difficult to assess the probability distribution of the tasks; it is also quite unlikely that the designer and the actual members of the organization have the same perception of the tasks' probability distribution. In this chapter, this assumption is relaxed: it is assumed that the designer knows the tasks' real probability distribution, while the organization members have a different perception of this distribution. The second assumptions about common perception of task value is also improbable: the decisionmakers in the organization may assign different value to the various tasks from the ones the designer assumed. The relaxation of this assumption is also presented in Chapter 3.

In order to pose both problems properly, two additional assumptions must be made. The first is trivially true in practice, but needs to be made explicit in the mathematical analysis: there is no communication between the designer and the organization members. The second assuption is that the

designer knows both the true task uncertainty and the uncertainty as perceived by each of the organization members, as well as both the true value of the tasks and the value assigned to the tasks by each decisionmaker. This information is needed in order to carry out sensitivity analyses. The theoretical development is then applied to two three-person organizations, a hierarchical and a parallel one, in order to illustrate the sensitivity analysis and its use in selecting organizational designs.

The same effectiveness analysis methodology, but with different measures of performance, can be applied to the evaluation of the architecture of command and control systems. Such an application to a model abstracted from an actual US Army system is presented in Chapter 4.

Finally, in the concluding chapter, the results are summarized and suggestions for further research are made.

2. THE INTERACTING DECISIONMAKER MODEL

The first step in modeling an organizational structure is the modeling of the tasks to be performed by the organization. The second step is to develop an appropriate mathematical model of the organization member. Specifically, this model must incorporate provisions for the variety of interactions that can exist among decisionmakers in an organization. These two steps are discussed in this chapter. In addition, the necessary analytical tools are introduced, namely, Petri Nets and N-dimensional information theory. The former is used to describe, rather precisely, the architecture of the decisionmaking model, and of the organizations, while the latter is used to model the cognitive workload of the individual decisionmakers.

2.1 PETRI NETS

In this work, only the basic properties of Petri Nets are needed to describe the models. In related work for the Office of Naval Research and for the Technical Panel on C^3 of the Joint Directors of Laboratories, several measures of performance (MOPs) of organizations have been obtained using some more advanced concepts from Petri Net theory [4,5]. For an introductory treatment of Petri Nets as modeling tools, the text by Peterson [6] is recommended.

Petri Nets are bipartite directed graphs reprsented by a quadruple (P,T,I,O). By convetion, P is the set of one type of nodes, called places or circle nodes, and T is the set of the second type of nodes, called transitions or bar nodes. Places can depict the presence of signals or represent conditions; transitions can depict processes or events. Consequently, the arcs that connect the nodes that form the graph can only go from one type of node to another - either from a place to transitions, or from a transition to places. The mapping I corresponds to the set of directed arcs from places to transitions, i.e., it defines the input places of the transitions, while the mapping O corresponds to the set of directed arcs from transitions to places; i.e., it defines the output places of each transition. For ordinary Petri Nets - the only type considered here - the mappings I and O take values from the closed set {0,1}; 1 denotes the presence of a link between two nodes, while 0 denotes the absence.

A Petri Net consisting of four transitions and five places is shown in Figure 2.1. Tokens, denoted by dots in places or circle nodes, control the execution of a Petri Net. A marking of a Petri Net is a mapping which assigns a non-negative integer number of tokens to each place of the net. Since the number of tokens in a place, in general, is not bounded, there can be an infinite number of markings associated with each net. A Petri Net is said to execute when a transition fires. A transition can fire, only if it is enabled. For a transition to be enabled, all its input places must contain at least one token each. When a transition fires, it removes one token from each input place and creates a new token in each of the output places of that transition. One can envision a sequence of firings in the Petri Net of Figure 2.1: Let the initial marking consist of a token in the first (left

most) place. Then the first transition is enabled and it fires. The token in
the first place is removed and a token appears in the second place. Now the
second transition is enabled: it fires and the token is removed from the
second place; a new one appears in the third place, and so on. The execution
halts when the fourth transition fires and a token appears on the fifth place.
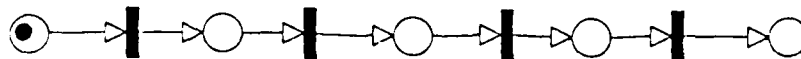
Figure 2.1. A Simple Petri Net

A transition may have more than one output places. When it fires, a
token is generated in each output place. However, to model decision making,
it is convenient to introduce a special transition, a decision switch, in
which the output places represent alternatives. When the decision switch
fires, a token is generated in only one of the output places. A decision rule
associated with this special transition determines the place in which the
token is generated. The rule can be deterministic or stochastic; it can be
independent of the attributes of the tokens in the input places or it may
depend on them.

A subnet of a Petri Net PN is a Petri Net PN_s with places P_s that are a
subset of the places P of the original net and transitions T_s that are a
subset of the transitions T of the original net. The input and output
mappings, I_s and O_s, are restricted to the arcs between the subsets T_s and P_s.
The use of subnets simplifies the graphical representation of complex
organizations and allows the depiction of the decisionmaker model at a level
of detail appropriate to the problem being solved.

2.2 INFORMATION THEORY

Information theory was first developed as an application in communication
theory [7]. But, as Khinchin [8] showed, it is also a valid mathematical
theory in its own right, and it is useful for applications in many
disciplines, including the modeling of simple human decisionmaking processes
and the analysis of information-processing systems.

There are two quantities of primary interest in information theory. The
first of these is _entropy_: given a variable x, which is an element of the
alphabet X, and occurs with probability p(x), the entropy of x, H(x), is
defined to be

$$H(x) = - \sum_x p(x) \ \log p(x) \tag{2.1}$$

and is measured in bits when the base of the algorithm is two. The other

quantity of interest is <u>average mutual information</u> or <u>transmission</u>: given two variables x and y, elements of the alphabets X and Y, and given p(x), p(y), and p(x|y) (the conditional probability of x, given the value of y), the transmission between x and y, T(x:y) is defined to be

$$T(x:y) \equiv H(x) - H_y(x) \qquad (2.2)$$

where

$$H_y(x) \equiv - \sum_y p(y) \sum_x p(x|y) \log p(x|y) \qquad (2.3)$$

is the conditional uncertainty in the variable x, given full knowledge of the value of the variable y.

McGill [9] generalized this basic two-variable input-output theory to N dimensions by extending Eq. (2.2):

$$T(x_1:x_2:\ldots:x_N) \equiv \sum_{i=1}^{N} H(x_i) - H(x_1,x_2,\ldots,x_N) \qquad (2.4)$$

For the modeling of memory and of sequential inputs which are dependent on each other, the use of the entropy rate, $\bar{H}(x)$, which describes the average entropy of x per unit time, is appropriate:

$$\bar{H}(x) \equiv \lim_{m \to \infty} \frac{1}{m} H[x(t), x(t+1),\ldots,x(t+m-1)] \qquad (2.5)$$

The transmission rate, $\bar{T}(x:y)$, is defined exactly like transmission, but using entropy rate in the definition rather than entropy.

The Partition Law of Information [10] is defined for a system with N-1 internal variables, w_1 through w_{N-1}, and an output variable, y, also called w_N. The law states

$$\sum_{i=1}^{N} H(w_i) = T(x:y) + T_y(x:w_1,w_2,\ldots,w_{N-1}) + T(w_1:w_2:\ldots:w_{N-1}:y)$$

$$+ H_x(w_1,w_2,\ldots,w_{N-1},y) \qquad (2.6)$$

and is easily derived using information theoretic identities. The left-hand side of Eq. (2.6) refers to the total activity of the system, also designated by G. Each of the quantities on the right-hand side has its own interpretation. The first term, $T(x:y)$, is called __throughput__ and is designated G_t. It measures the amount by which the output of the system is related to the input. The second quantity,

$$T_y(x:w_1,w_2,\ldots,w_{N-1}) = T(x:w_1,w_2,\ldots,w_{n-1},y) - T(x:y) \tag{2.7}$$

is called __blockage__ and is designated G_b. Blockage may be thought of as the amount of information in the input to the system that is not included in the output. The third term, $T(w_1:w_2:\ldots:w_{N-1}:y)$ is called __coordination__ and is designated G_c. It is the N-dimensional transmission of the system, i.e., the amount by which all of the internal variables in the system constrain each other. The last term, $H_x(w_1,w_2,\ldots,w_{N-1},y)$, designated by G_n represents the uncertainty that remains in the system variables when the input is completely known. This noise should not be construed to be necessarily undesirable, as it is in communication theory: it may also be thought of as __internally-generated information__ supplied by the system to supplement the input and facilitate the decisionmaking process. The partition law may be abbreviated:

$$G = G_t + G_b + G_c + G_n \tag{2.8}$$

A statement completely analogous to (2.8) can be made about information rates by substituting entropy rate and transmission rates in Eq. (2.6).

2.3 TASK MODEL

The organization, interacts with its environment; it receives signals or messages in various forms that contain information relevant to the organization's tasks. These messages must be identified, analyzed, and transmitted to their appropriate destinations within the organization. From this perspective, the organization acts as an information user.

Let the organization receive data from one or more sources (N') external to it. Every τ_n units of time on the average, each source n generates symbols, signals, or messages x_{ni} from its associated alphabet X_n, with probability p_{ni}, i.e.,

$$p_{ni} = p(x_n = x_{ni}) \quad ; \quad x_{ni} \in X_n \quad i = 1,2,\ldots,\gamma_n \tag{2.9}$$

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$$\sum_{i=1}^{\gamma_n} p_{ni} = 1 \quad ; \quad n = 1,2,\ldots,N' \qquad (2.10)$$

where γ_n is the dimension of x_n. Therefore, $1/\tau_n$ is the mean frequency of symbol generation from source n.

The organization's task is defined as the processing of the input symbols x_n to produce output symbols. This definition implies that the organization designer knows a priori the set of desired responses Y and, furthermore, has a function or table $L(x_n)$ that associates a desired response or a set of desired responses, elements of Y, to each input $x_{ni} \; \varepsilon \; X_n$.

It is assumed that a specific complex task that must be performed can be modeled by N' sources of data. Rather than considering these sources separately, one supersource, composed of these N' sources, is created. The input symbol $\underline{x}'$ may be represented by an N'-dimensional vector with each source corresponding to a component of this vector, i.e.,

$$\underline{x}' = (x_1, x_2, \ldots, x_{N'}) \quad ; \quad \underline{x}' \; \varepsilon \; X \qquad 2.11)$$

To determine the probability that symbol $\underline{x}'_j$ is generated, the independence between components must be considered. If all components are mutually independent, then p_j is the product of the probabilities that each component of $\underline{x}'_j$ takes on its respective value from its associated alphabet. If two or more components are probabilistically dependent on each other, but as a group are mutually independent from all other components of the

$$p_j = \prod_{n=1}^{N'} p_{nj} \qquad (2.12)$$

input vector, then these dependent components can be treated as one supercomponent, with a new alphabet. Then a new input vector, $\underline{x}$, is defined, composed of the mutually independent components and these super-components.

This model of the sources implies synchronization between the generation of the individual source elements so that they may, in fact, be treated as one input symbol. Specifically, it is assumed that the mean interarrival time τ_n for each component is equal to τ. It is also assumed that the generation of a particular input vector, $\underline{x}_j$, is independent of the symbols generated prior to or after it.

The last assumption can be weakened, if the source is a discrete stationary ergodic one with constant interarrival time τ that could be approximated by a Markov source. Then the information theoretic framework can be retained [11].

The vector output of the source is partitioned into groups of components that are assigned to different organization members. The j-th partition is denoted by $\underline{x}^j$ and is derived from the corresponding partition matrix $\underline{\pi}^j$ which has dimension $n_j \times N$ and rank n_j, i.e.,

$$\underline{x}^j = \underline{\pi}^j \underline{x}. \tag{2.13}$$

Each column of $\underline{\pi}^j$ has at most one non-zero element. The resulting vectors $\underline{x}^j$ may have some, all, or no components in common.

The set of partitioning matrices $\{\underline{\pi}^1, \underline{\pi}^2, \ldots, \underline{\pi}^n\}$ shown in Figure 2.2 specify the components of the input vector received by each member of the subset of decisionmakers that interact directly with the organization's environment. These assignments can be time invariant or time varying. In the latter case, the partition matrix can be expressed as

$$\pi^j(t) = \begin{cases} \pi_o^j & \text{for } t \ \varepsilon \ \{T\} \\ \\ 0 & \text{for } t \ \notin \ \{T\} \end{cases} \tag{2.14}$$

The times $\{T\}$ at which a decisionmaker receives inputs for processing can be obtained either through a deterministic (e.g., periodic) or a stochastic rule. The question of how to select the set of partition matrices, i.e., design the information structure between the environment and the organization, has been addressed by Stabile [12,13].
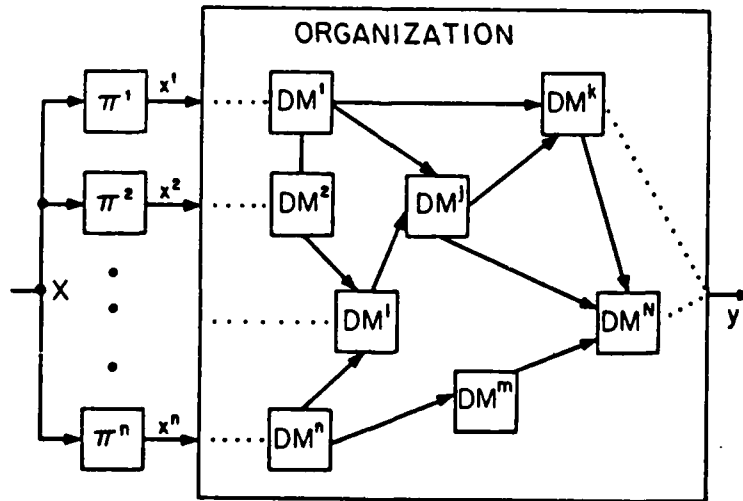
Figure 2.2. Information Structures for Organizations

2.4 THE DECISIONMAKER MODEL

The basic model of the memoryless decisionmaker with bounded rationality is based on the hypothesis of F. C. Donders [14] that information processing is done in stages. Specifically, it is assumed that the two stages are (a) situation assessment (SA), and (b) response selection (RS), which correspond to March and Simon's [15] two stage process of discovery and selection. The structure of this model, shown in Figure 2.3, has been extended to include interactions with other organization members, as well as memory. The extended model is shown in Figure 2.4.
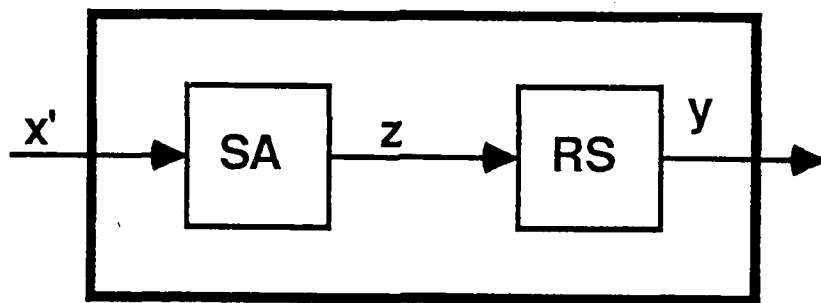
Figure 2.3   Two-Stage Model
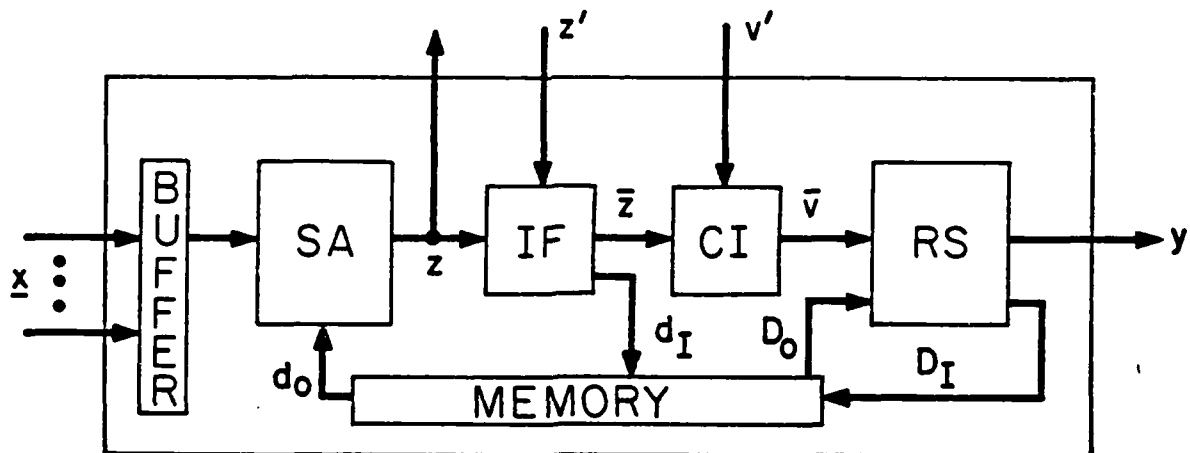
Figure 2.4   The Interacting Decisionmaker with Memory

The DM receives singals $x \, \varepsilon \, X$ from the environment with interarrival time τ. A string of signals may be stored first in a buffer so that they can be

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processed together in the situation assessment (SA) stage. The SA stage contains algorithms that process the incoming signals to obtain the assessed situation $\underline{z}$. The SA stage may access the memory or internal data base to obtain a set of values d_o. The assessed situation z may be shared with other organization members; concurrently, the DM may receive the supplementary situation assessment z' from other parts of the organization; the two sets z and z' are combined in the information fusion (IF) processing stage to obtain $\bar{z}$. Some of the data (d_I) from the IF process may be stored in memory.

The possibility of receiving commands from other organization members is modeled by the variable v'. A command interpretation (CI) stage of processing is necessary to combine the situation assessment $\bar{z}$ and v' to arrive at the choice $\bar{v}$ of the appropriate strategy to use in the response selection (RS) stage. The RS stage contains algorithms that produce outputs y in response to the situation assessment $\bar{z}$ and the command inputs. The RS stage may access data from, or store data in memory [11].

In this report, only the memoryless case is considered. Consequently, the general model reduces to the one shown Figure 2.5, where the Petri Net formalism has been used.
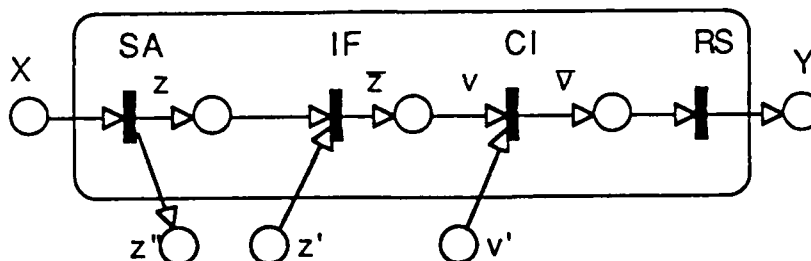
Figure 2.5. The Memoryless Interacting Decisionmaker Model

A more detailed description of the model is obtained, if the internal structure of the SA and RS stages is considered. The situation assessment stage consists of a set of U algorithms (deterministic or not) that are capable of producing some situation assessment z. The choice of algorithms is achieved through specification of the internal variable u in accordance with the situation assessment strategy p(u), or p(u|x), if a decision aid (e.g., a preprocessor) is present. A second internal decision is the selection of the algorithm in the RS stage according to the response selection strategy $p(\bar{v}|\bar{z},v')$. The two strategies, when taken together, constitute the internal decision strategy of the decisionmaker.

The subnets representing the SA and the RS stages are shown in Figure 2.6. Note the presence of decision switches in place of the regular transitions to indicate that only one of the output places can receive a token at each firing.
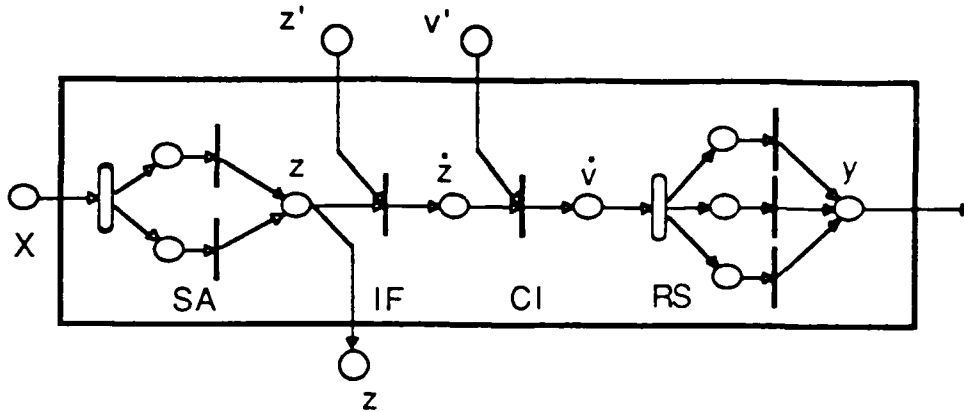
Figure 2.6. The SA and the RS Subnets

2.5 WORKLOAD

The analytical framework presented in Section 2.2, when applied to the single interacting decisionmaker with deterministic algorithms in the SA and RS stages, yields the four aggregate quantities that characterize the information processing and decisionmaking activity within the DM:

Throughput:

$$G_t = T(x,z',v':z,y) \tag{2.15}$$

Blockage:

$$G_b = H(x,z',v') - G_t \tag{2.16}$$

Internally generated information:

$$G_n = H(u) - H_{\bar{z}}(v) \tag{2.17}$$

Coordination:

$$G_c = \sum_{i=1}^{U} p_i g_c^i(p(x)) + a_i \, H(p_i) + H(z) + g_c^{IF} \, (p(z,z')) + g_c^{CI} \, (p(\bar{z},v')$$

$$+ \sum_{j=1}^{V} p_j g_c^i(p(\bar{z}|\bar{v} = j)) + a_j \, H(p_j) + H(y) + H(z) + H(\bar{z}) + H(\bar{z},\bar{v})$$

$$+ T_z(x':z') + T_{\bar{z}}(x',z':v') \tag{2.18}$$

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The expression for G_n shows that it depends on the two internal strategies $p(u)$ and $p(v|\bar{z})$ even though a command input may exist. This implies that the command input v' modifies the DM's internal decision after $p(v|\bar{z})$ has been determined.

In the expressions defining the system coordination, p_i is the probability that algorithm f_i has been selected for processing the input x and p_j is the probability that algorithm h_j has been selected, i.e., $u = i$ and $v = j$. The quantities g_c represent the internal coordinations of the corresponding algorithms and depend on the probability distribution of their respective inputs; the quantities a_i, a_j are the number of internal variables of the algorithms f_i and h_j, respectively. Finally, the quantity H is the entropy of a binary random variable that takes one of its two values with probability p.

$$H(p) = - p \log_2 p - (1 - p)\log_2(1-p) \tag{2.19}$$

Equations (2.15) to (2.18) determine the total activity G of the decisionmaker according to the partition law of information, Eq. (2.6). The activity G can be evaluated alternatively as the sum of the marginal uncertainties of each system variable. For any given internal decision strategy, G and its component parts can be computed.

Since the quantity G may be interpreted as the total information processing activity of the system, it can serve as a surrogate for the workload of the organization member in carrying out his decisionmaking task.

The qualitative notion that the rationality of a human decisionmaker is not perfect, but is bounded [16], has been modeled as a constraint on the total activity G. The specific form for the constraint has been suggested by the empirical relation

$$t = c_1 + c_2 G_t$$

where t is the average reaction time, i.e., the time between the arrival of the input and the generation of an output y. It is assumed that the decisionmaker must process his inputs at a rate that is at least equal to the rate with which inputs arrive. The latter has been modeled by τ, the mean symbol interarrival time:

$$t = c_1 + c_2 G_t \leq \tau$$

or

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$$\frac{1}{c_2} \ t = \frac{c_1}{c_2} + G_t \le \frac{1}{c_2} \ \tau$$

The modeling assumptions in this paper are that

$$\frac{c_1}{c_2} = G_b + G_n + G_c$$

and that c_2 does not depend on $p(x)$. Then, the bounded rationality constraint takes the form

$$G = G_t + G_b + G_n \quad G_c \ \le \ \frac{1}{c_2} \tau = F\tau \tag{2.20}$$

where F can be considered as a rate of total activity and is measured in bits per second. Inequality (2.20) represents a mathematical expression of only one aspect of bounded rationality. Many other formulations are possible.

Weakening the assumption that the algorithms are deterministic changes the numerical values of G_n and of the coordination term G_c [17]. If memory is present in the model, then additional terms appear in the expressions for the coordination rate and for the internally generated information rate [11].

2.6 MEASURES OF PERFORMANCE

As stated in Section 2.3, it is assumed that the designer knows a priori the set of desired responses Y to the input set X. One measure of performance (MOP) of the organization that reflects the degree to which the actual response matches the desired response can be computed as shown in Figure 2.7.
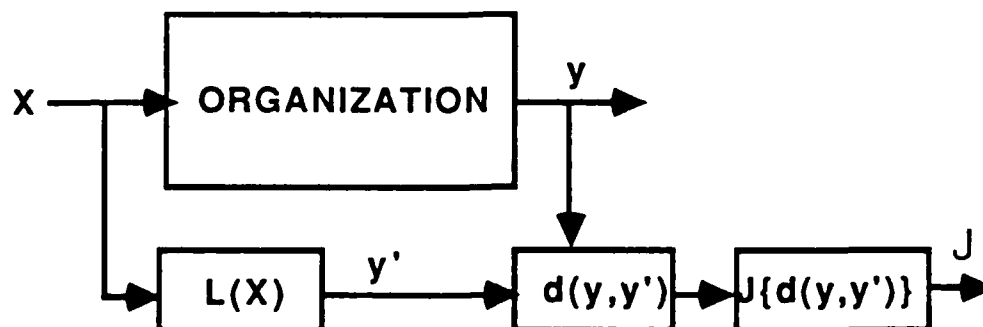

Figure 2.7. Performance Evaluation of an Organization

The decisionmaker's actual response y can be compared to the desired response y' and a cost is assigned using the cost function d(y,y'). If this function is a binary one, i.e.,

$$d(y,y') = \begin{cases} 0 & \text{if } y = y' \\ 1 & \text{if } y \neq y' \end{cases} \tag{2.21}$$

then the expected value of this cost denotes the probability that the wrong decision is made, i.e., it is the probability of error.

In general, however, there is a cost c_{ij} associated with selecting $y_i \in Y$ when the desired response is $y_j \in Y'$:

$$c_{ij} = d(y_i, y_j') \tag{2.22}$$

so that

$$J = \sum_j p(x_j) \sum_i c_{ij} p(y_i | x_j) \tag{2.23}$$

where y_j' is the desired response to task x_j. This measure of performance can be interpreted as a measure of the <u>accuracy</u> of the response, to the extent that a cost is associated with the degree with which the actual decision deviates from the desired one.

This class of performance measures, described generically by (2.23), is not the only one that has been considered. In related work [18], measures of performance that address time have been modeled and analyzed.

2.7 PERFORMANCE-WORKLOAD LOCUS

A useful way of describing the properties of the decisionmaker model, which is generalizable to the properties of an organization, is through the performance workload locus. In the case of a single performance measure, the accuracy measure J, and a single decisionmaker with workload G, a two dimensional space is defined with ordinate J and abscissa G. The locus is constructed by considering the functional dependence of J and G on the internal decision strategies of the single decisionmaker.

Let an internal strategy for a given decisionmaker be defined as pure, if both the situation assessment strategy p(u) and the response selection strategy $p(v|Z)$ are pure, i.e., an algorithm f_i is selected with probability one and an algorithm h_j is selected also with probability one when the situation is assessed as being Z:

$$D_k = \{p(u=i) = 1 \quad ; \quad p(v=j|\bar{z}=\bar{Z}) = 1\} \tag{2.24}$$

for some i, some j, and for each $\bar{Z}$ element of the alphabet $\bar{Z}$. There are n possible pure internal strategies,

$$n = U \cdot V^M \tag{2.25}$$

where U is the number of f algorithms in the SA stage, V the number of h algorithm in the RS stage and M the dimension of the set $\bar{Z}$. All other internal strategies are mixed [1] and are obtained as convex combinations of pure strategies:

$$D(p_k) = \sum_{k=1}^{n} p_k D_k \tag{2.26}$$

where the weighting coefficients are probabilities.

Corresponding to each $D(p_k)$ is a point in the *simplex*

$$\sum_{k=1}^{n} p_k = 1, \quad p_k \geq 0 \quad \forall k \tag{2.27}$$

The possible strategies for an individual DM are elements of a closed convex polyhedron of dimension n−1 whose vertices are the unit vectors corresponding to pure strategies.

The total activity G, the surrogate for the cognitive workload, is a convex function of the decision strategy, i.e.,

$$G(D(p_k)) \geq \sum_{k=1}^{n} p_k G_k \tag{2.28}$$

where G_k is the workload that results when the pure strategy D_k, given by Eq. (2.24), is used.

The accuracy measure J can be related to the decision strategies in a similar manner. Corresponding to each pure strategy D_k is a value of the performance measure, denoted by J_k. Since each strategy is a convex

combination of pure strategies, the value of J for an arbitrary $D(p_k)$ is given as a convex combination of the values of J_k, i.e.,

$$J(D(p_k)) = \sum_{k=1}^{n} p_k J_k \qquad (2.29)$$

The two expressions, (2.28) and (2.29) can be used now to characterize the locus of points in the (J,G) space that describe the decisionmaker.

Example: Consider first the case of two pure strategies, D_1 and D_2. This would correspond to the case where the decisionmaker can choose only between two different algorithms f in the SA stage, as shown in Figure 2.8. The strategy space for this case can be parametrized as follows: Any strategy, D, can be expressed as

$$D = p_1 D_1 + p_2 D_2 \qquad (2.30)$$

where $\quad p_1 + p_2 = 1$

in accordance with (2.26) and (2.27). Let

$$p_1 = 1 - \delta \quad \text{and} \quad p_2 = \delta$$

and let

$$0 \leq \delta \leq 1$$

Then, (2.30) can be rewritten as

$$D = (1-\delta) D_1 + \delta D_2 \qquad (2.31)$$
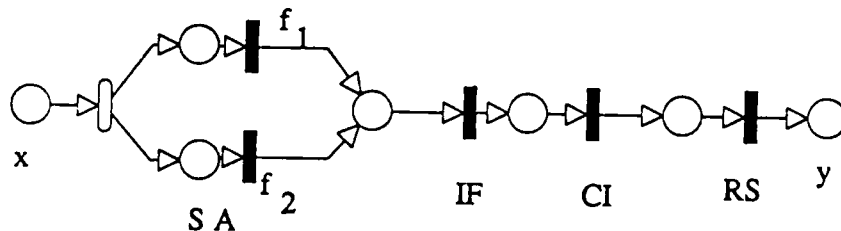
Figure 2.8. The Petri Net for the Example

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The strategy space can be described by the parameter δ: it is the line segment [0,1], as shown in Figure 2.9, with the point 0 corresponding to pure strategy D_1, point 1 to pure strategy D_2, and all points in between to all the mixed strategies.
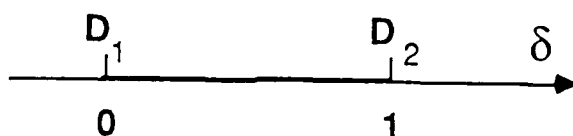
Figure 2.9. Strategy Space for Example

Then, it follows from (2.28) and (2.29) that

$$G(D(p_k)) = G(D(\delta)) \geq (1-\delta)G_1 + \delta\, G_2 \qquad (2.32)$$

and

$$J(D(p_k)) = J(D(\delta)) = (1-\delta)J_1 + \delta\, J_2 \qquad (2.33)$$

Equations (2.32) and (2.33) are parametric in δ and result in the locus shown in Figure 2.10. The relative position of the end points (J_1,G_1) and (J_2,G_2) is problem specific; it is not true that smaller workload leads to worse performance, as Figure 2.10 indicates.
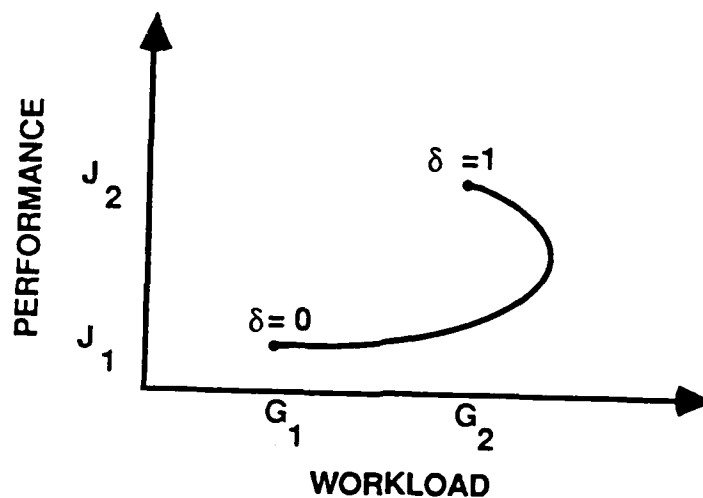
Figure 2.10. Performance-Workload Locus for Example

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In the general case, there are n pure strategies, as given by Eq. (2.25). Then, the P-W locus is constructed as follows:

First, the values of (J_i, G_i) for the n pure strategies are determined. This corresponds to evaluating the performance and the workload for the values of p_k, Eq. (2.27), that correspond to the vertices of the strategy space. The result is a set of n points in the two-dimensional P-W space.

Then, the binary variations between each possible pair of pure strategies are considered. This corresponds to the mapping of the edges of the strategy space. For example, consider pure strategies D_i and D_k; then

$$D = (1-\delta)D_i + \delta D_k$$

for all combinations (i,k) where i=1,...,n and k=1,...,n and for which i≠k. By varying δ from 0 to 1, the loci $(J_{ik}(\delta), G_{ik}(\delta))$ are obtained. These are convex lines joining the two boundary points, as shown in Figure 2.10. These binary loci are quite useful, since they define the minimum workload locus for any feasible value of J.

The third step consists of considering, successively, the binary variation between all possible binary strategies until all mixed strategies are accounted for. The result is a locus such as the one shown in Figure 2.11 for the case when there are three pure strategies. The corresponding strategy space, for this case, is shown in Figure 2.12.
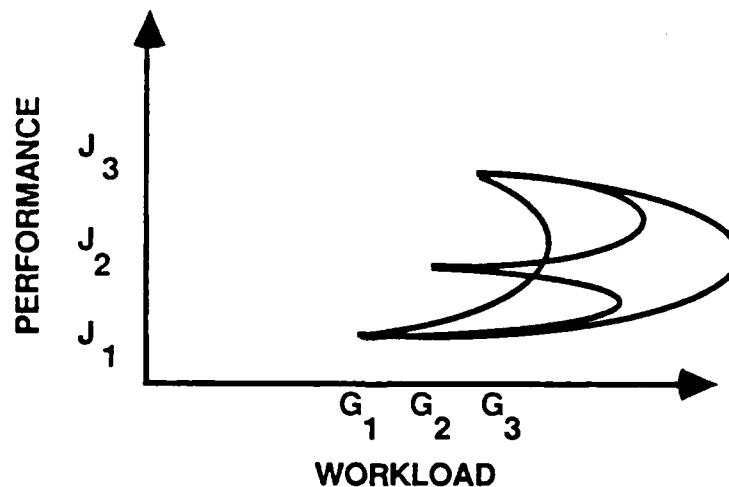
Figure 2.11. Performance-Workload Locus for the Case of Three Pure Strategies

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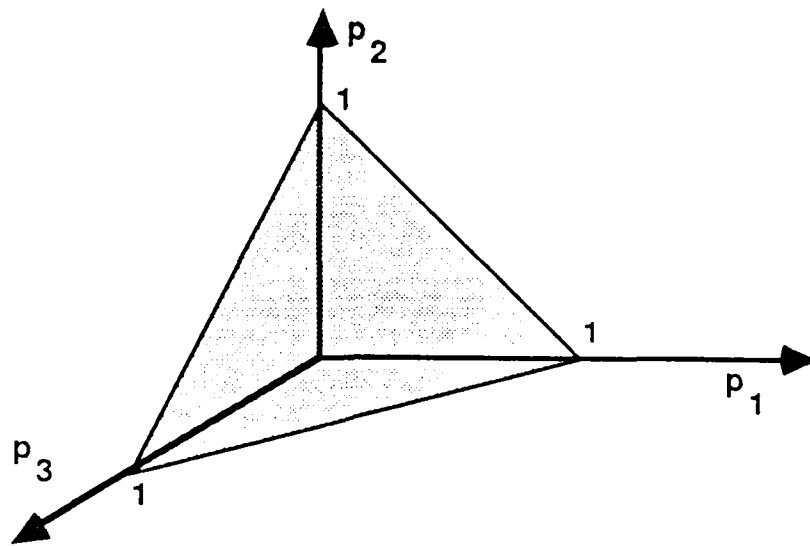
Figure 2.12. Strategy Space for the Case of Three Pure Strategies

Thus, the decisionmaker model can be considered as a system that maps the strategy locus, the simplex defined by Eq. (2.27), into the Performance-Workload Locus (J,G). Any change in the algorithms f or h, or the functions in IF and CI, or the input x will affect the mapping.

Any specific instantiation of the decisionmaker model can be analyzed by considering the strategy space and the corresponding P-W locus. The detailed procedure for doing both a qualitative and a quantitative evaluation will be presented in the next chapter.

3. THE DESIGNER'S AND THE DECISIONMAKERS'S POINTS OF VIEW[*]

When the tasks which have to be performed exceed the capabilities of a single person, organizations are formed, consisting of individuals interacting with each other in specific ways. The most important characteristic of the organizations considered here is that their task involves information processing and decisionmaking.

In earlier work [1-3], several simplifying assymptions has been made in the design and analysis of decisionmaking organizations: (a) designers and decisionmakers have identical knowledge of the tasks' uncertainty, i.e., the probability distribution of the tasks and (b) identical perception of the value of each task. These assumptions are very restrictive and often unjustifiable. In general, it is very difficult to assess the probability distribution of the tasks; it is also unlikely that the designer and the decisionmakers have the same perception of the tasks' probability distribution. In this chapter, this assumption is relaxed.

It is assumed that the designer knows the tasks' real probability distribution, while the decisionmaker's peception of this distribution is different. The second assumption, that all tasks are of equal value, is also improbable; usually, different tasks have different utilities, i.e., different weights are assigned to them by the designer. Therefore, the second assumption must be weakened, so that each task can be weighted differently. In order to pose these problems properly, two additional assumptions must be introduced: (a) there is no communication between the designer and the decisionmakers and (b) the designer knows the tasks' uncertainty as perceived by each decisionmaker in the organization, as well as the relative weights assigned by them to each task.

3.1 THE ORGANIZATION MODEL

The task consists of receiving data (signals), processing that data, and producing an output in the form of actions or signals. The input data can originate from a single source or from many different sources as described in the previous chapter. The data may be a single element or a set of elements. In general, it is modeled as a vector, x, generated by a single source. This vector signal is partitioned by partitioning matrices π and allocated to the appropriate decisionmakers. A task can be specified fully by its finite scheme, which consist of the task's alphabet and its probability distribution, i.e.,

$$X = (X, P) = \begin{pmatrix} x_1 & x_2 & \cdots & x_m \\ p_1 & p_2 & \cdots & p_m \end{pmatrix} \qquad (3.1)$$

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[*]This section is based on the work of M. M. Tomovic [18]; the computational results have been revised recently by J. Azzola.

The basic model of the memoryless decisionmaker introduced in the previous chapter will be used. It is assumed that the overall task x is partitioned by the matrix π^n and that only the appropriate elements of x are allocated to the n-th decisionmaker. The decisionmaker processes the data using the algorithms in the SA stage in order to assess the situation. The assessed situation, $\bar{z}^n$, is then processed in the RS stage, where the decision of an appropriate action or response, y^n, is made. Which ones of the SA and RS algorithms a decisionmaker will use depends on his choice of internal decision strategy, D_k^n. For the situation assessment stage, it is assumed that the strategy u^n is independent of the input x^n, whereas in the response selection stage v^n depends on the value of the assessed situation $\bar{z}^n$. THe assumption that the choice of u^n is not dependent on x^n has been relaxed by Chyen and Levis [17].

In order to make communication and interaction between decisionmakers possible, the information fusion (IF), and the command interpretation (CI) elements have been included. The IF process allows sharing of the information on the state of environment between decisionmakers. This functional element associates information on the assessed situation obtained by the n-th decisionmaker, z^n, and the corresponding information sent to him from the rest of organization, z^{on}, and gives the cumulative updated information on the state of environment $\bar{z}^n$. It is also possible for the n-th decisionmaker to communicate his knowledge on the state of environment z^{no} to other members of the organization, who accept and fuse that information with their own in the corresponding IF stage. Commands v^{on} received by the n-th decisionmaker from the rest of the organization can modify or even override his own decision v^n.

3.2 WORKLOAD AND PERFORMANCE

The concepts of decision stategies, workload, and performance introduced in Chapter 2 for the single decisionmaker need to be generalized to apply to organizations consisting of a number of decisionmakers operating as a team of accomplish the given set of tasks. As before, the two fundamental quantities are the workload or the activity level of each individual DM and the performance index of the organization. Both of them are functions of the input, the decisionmaker's internal structures, the organization's protocol or standard operating procedures and the decision strategies. For a specified input, a protocol and an internal structure (set of algorithms) both the performance and the workload depend parametrically on the organizational behavioral strategy which is defined as

$$\Delta = \{D^1(p^1), \ldots, D^N(p^N) = \sum_{k^1} \ldots \sum_{k^N} \Delta_{k^1 \ldots k^N} \; p_k^1 \ldots p_K^N \qquad (3.2)$$

where $D^n(p^n)$ is the n-th decisionmaker's mixed decision strategy, and $\Delta_{k^1, \ldots, k^N}$ denotes a pure strategy of the organization (see Levis and Boettcher [2]).

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The surrogate workload for each decisionmaker is defined as the activity necessary to reduce uncertainty and arrive at a decision. For each DM it is defined as

$$G^n = G^n(\Delta) = - \sum_i \sum_j p(w^i_{jn}) \log p(w^i_{jn}) \tag{3.3}$$

where w^i_{jn} is the j-th value of the i-th internal variable of the n-th decisionmaker. When the tasks' finite scheme X, organizational structure (algorithms and protocols) and organization's behavioral strategy Δ, Eq. (3.2), are specified, it is then possible to evaluate the activity of each decisionmaker within the organization.

In has been shown in Chapter 2 that the total activity G is a convex function of the decision strategy Δ in the sense that

$$G(\Delta) \geq \sum_{k^1} \dots \sum_{k^N} G(\Delta_{k^1 \dots k^N}) p_{k^1} \dots p_{k^N} \tag{3.4}$$

where $G(\Delta_{k^1 \dots k^N})$ is the workload corresponding to the pure strategy.

The bounded rationality of each decisionmaker is modeled as a constraint on his total activity

$$G^n(\Delta) \leq F^n \tau \tag{3.5}$$

where F^n is the maximum rate at which the n-th decisionmaker can process information and τ is the mean interarrival time of tasks.

The organization's performance is defined as

$$J = E\{d(y,y')\} = \sum_i p(x_i) \sum_j d(y_j, y'_j) p(y_j | x_i) \tag{3.6}$$

where y_j is the actual output of the organization as a whole in response to the input x_i and where y_j is the designer. As in the case of a single decisionmaker, the comparison function $d(y,y')$ can take any form appropriate to the particular problem; in its simplest form it is defined as

$$d(y,y') = \begin{cases} 0 & , \quad y = y' \\ 1 & , \quad y \neq y' \end{cases} \tag{3.7}$$

In that case, the performance index is reduced to the probability of producing an incorrect response, i.e., the probability of making an error.

The performance measure has meaning only for the organization as a whole and can be expressed as

$$J(\Delta) = \sum_{k^1} \ldots \sum_{k^N} J_{k^1 \ldots k^N} \, p_{k^1}^1 \ldots p_{k^N}^N \tag{3.8}$$

to show its dependence on the choice of an organizational strategy. The designer is the one who assigns the value of the performance threshold $(\bar{J})$ which the decisionmaking organization has to meet, i.e.,

$$J(\Delta) \leq \bar{J} \tag{3.9}$$

This condition determines the set of strategies that yield satisficing performance.

3.3 THE PERFORMANCE-WORKLOAD LOCUS

For each decision strategy, the organization's performance and the workload of each of the N decisionmakers can be computed using the algorithms first developed by Boettcher [20], revised by M. Tomovic [19] and then completely revised by Andreadakis [18] as part of the Computer-Aided Evaluation of System Architectures (CEASAR) workstation. The performance-workload locus, S_o, is defined in the (N+1)-dimensional space S as the set of all points $(J, G^1, \ldots, G^N)$ that correspond to the set of all admissible decision strategies. Let $\sum$ be the set of all admissible strategies of the organization; then

$$\sum = \sum (\sum^1, \sum^2, \ldots, \sum^N) \tag{3.10}$$

where $\sum^n$ is the set of admissible strategies of the n-th decisionmaker.

The bounded rationality contrainst for each DM, Eq. (3.5) is expressed simply as a bounding hyperplane in the performance-workload space; the satisficing constraint, Eq. (3.9), is also a bounding hyperplane that intersects the J axis at $\bar{J}$.

The resulting performance-workload locus can be used to compare

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qualitatively two different organizational structures or designs that are to perform the same task. It can also be used to compare the effectiveness of the same organization in dealing with different degrees of uncertainty, i.e., for different probability distributions of the input alphabet X, the set of tasks. This qualitative analysis is based on how well the locus S_0 meets the requirements of Eqs. (3.5) and (3.9).

A quantitative approach to the comparison and effectiveness analysis of organizational forms is based on comparisons not in the performance-worklaod space, but in the strategy space. Bounded rationality contraints, Eq. (3.5), and performance requirements , Eq. (3.9), partition the space of organization strategies into a set of strategies that lead the points in the performance-workload locus that satisfy constraints Eqs. (3.5) and (3.9), and a set that does not. The set of feasible strategies is defined as follows:

$$\Sigma' = \Sigma \ \{\Delta | J(\Delta) \leq \bar{J}, \ G^2(\Delta) \leq F^1\tau, \ldots, G^N(\Delta) \leq F^N\tau\} \tag{3.11}$$

Then, a measure of effectiveness, Q, called the consistency measure, can be defined [3]:

$$Q = V(\Sigma')/V(\Sigma) \tag{3.12}$$

where V is a volume in the N-dimensional strategy space. Therefore, Q denotes the fraction of all strategies that are feasible. The higher it is, the more consistent the decisions of the organization will be in the design specifications. A second interpretation of the measure is the following: if all organizational decision strategies are equally probable, then Q is the probability that the organization will make a decision that satisfies the individual bounded rationality constraints and leads to satisficing performance. Hence, Q is a bounded non-decreasing function of the performance threshold $\bar{J}$ and individual decisionmaker's activity threshold $F^n\tau$, (n=1,...,N).

$$0 \leq Q(\bar{J}, F^1\tau, \ F^2\tau, \ldots, F^N\tau) \leq 1 \tag{3.13}$$

The consistency measure Q is equal to zero, if there is no decision strategy which meets the specifications of the task. Its value is equal to unity, if all admissible decision strategies satisfy the requirements. It is evident that the higher value of the mutual consistency measure Q, the better performance can be expected from that system. Therefore, the designer can compare systems with respect to Q and select the one with the highest value of Q for a given $\bar{J}$ and τ.

A more useful representation of Q is in terms of the performance threshold $\bar{J}$ and the mean interarrival time τ. The resulting expression

$$0 \leq Q(\bar{J},\tau) \leq 1 \qquad\qquad (3.14)$$

can be depicted in a three-dimensional space regardless of the size of the organization.

3.4 TWO POINTS OF VIEW

The basic premise in earlier work is that the designer knows the finite scheme, Eq. (3.1), and the performance index and that he assumes the decisionmakers in the organization will have the same knowledge. On that basis, he can design an organizational form and evaluate it. However, the question arises as to how robust the design is, i.e., how sentitive is the value of Q to the assumption that the decisionmakers have indeed the same knowledge. Suppose, that they have different perceptions of the tasks' uncertainty and they assign different values to the inidividual tasks. The inidivudal decisionmakers who only receive partial information about the organization's tasks may have a different perception of the probability distribution $p(x)$. Furthermore, their local objectives may distort the values of the weights assigned to each task by the designer who maintains a global perspective.

The designer can adopt two points of view in order to study the robustness of his design. First, he can assume that the DMs will operate on the basis of his perception of task uncertainty, $p(x)$, and objective function J. Or, he can assume that the DMs will operate on the basis of a different perception of task uncertainty, e.g., $q(x)$, and that they will assign different values, $c(x)$, to the various tasks x_i.

These two points of view lead to the formualtion of four problems that the designers must analyze.

Problem 1: (Basic Problem) The DMs know the objective probability distribution of the tasks, $p(x)$, and the weighting coefficients for the various tasks. For simplicity, it is assumed that all the coefficients $c(x)$ are equal to unity for the base case.

Problem 2: (Task Uncertainty) The DMs have their own perception of the probability distribution of the input, $q(x)$, instead of $p(x)$, but assign the same values to the tasks as the designer ($c(x) = 1$).

Problem 3: (Task Value) The DMs know the objective probability distribution to the tasks, $p(x)$, but assign different values of the various tasks, i.e., their $c(x)$ differs from the designer's ($c(x) \neq 1$).

Problem 4: (General Problem) The DMs have their own perception of the probability distribution of the input, $q(x)$, and the value of the tasks ($c(x) \neq 1$).

Problem 1 is the one that has been analyzed in detail in [1],[2], and [3] while Problem 4 is the general case: Problems 1, 2, and 3 are really special cases of 4. In this study, Problem 2 is analyzed because it addresses the complex interrelationship between uncertainty and workload.

It is possible to develop the analytical expressions for the workload as a function of $p(x)$ and of $q(x)$. It is also possible to introduce weighted entropy [21], and derive the expressions for the difference in the workload G^n due to the difference in the perception of the task uncertainty by the designer and the decisionmakers. However, the analytical expressions have not yielded any particular insight to the problem. Consequently, the sensitivity analysis will be described in terms of an example.

3.5 TWO THREE-PERSON ORGANIZATIONS

Two three-person organizations have been used to illustrate the analysis and comparison of alternative organizational forms. This simple example has been based on the problem of designing the organization of batteries of surface-to-air missiles.

Let the trajectory of a target be defined by an ordered pair of points located in a rectangle that represents a two-dimensional (flat) sector of airspace. From the ordered pair, the speed and direction of flight of the target can be determined. On the basis of that information, the organization should respond by firing either a slow or a fast surface-to-air missile or by not firing at all. It is assumed that the size of that sector, the frequency of the arrival of targets, and the response time of the weapons systems are such that three units are needed, i.e., it is necessary to design a three-member organization to accomplish the task. Two such organizational structures are considered.

The first structure, Organization A, is a parallel structure with lateral links, and is defined as follows. The rectangular sector is divided into three equal subsectors and a decisionmaker is assigned to each one, see Figure 3.1. Each DM is capable of observing only the points that appear in his subsector. He can assess the situation, i.e., estimate the trajectory, and select the response, i.e., which weapons to fire, for targets with trajectories totally within his subsector. This is the case when two points that define the target are within his subsector. Since it is possible for trajectories to "straddle" the subsector boundaries, it is necessary that SA information be shared. Thus, DM^1 and DM^2 share information that relates to their common boundary. Similarly, DM^2 and DM^3 share information that relates to targets that cross their common boundary. To keep the example computationally simple, the situation assessment stages of DM^1 and DM^2 are assumed to contain a single algorithm f^n; that of DM^2 contains two algorithms f_1^2 and f_2^2. In contrast, the response selection stage of DM^2 contains a single algorithm h^2, while the RS stages of DM^1 and DM^3 contain two algorithms h_1^n and h_2^n, $n = 1,3$. Therefore, the internal decision strategies are $p(u^2)$, $p(v^1|z^1)$, and $p(v^3|z^3)$. The detailed structure of this organization is shown in Figure 3.2. Note that the interactions defined by the information structure exhibit
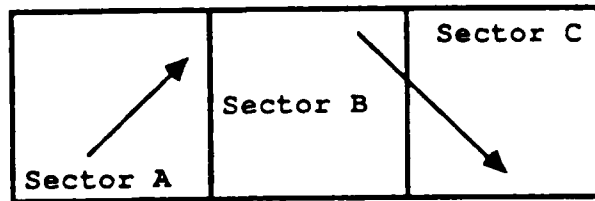
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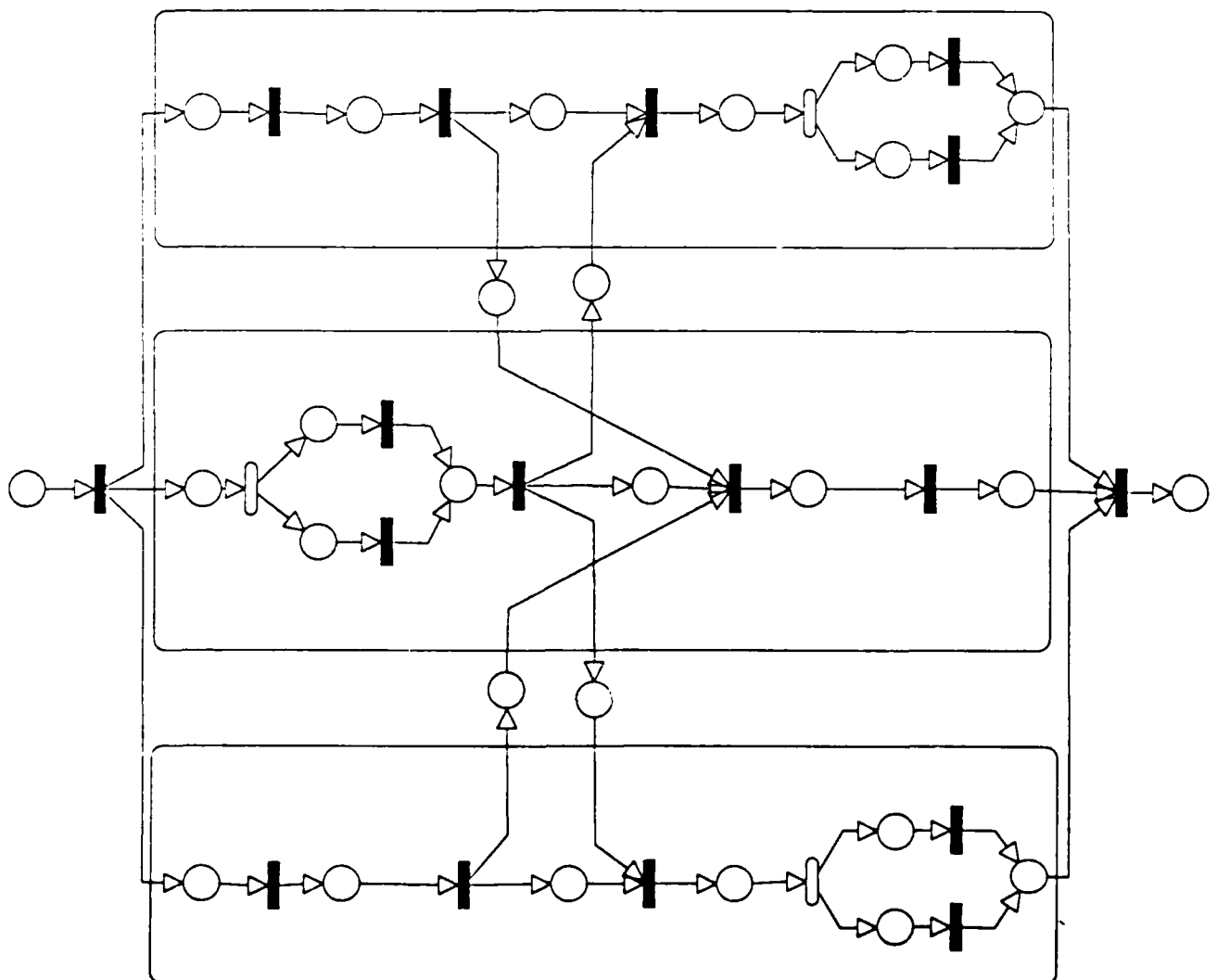Figure 3.1. Three Sectors (Parallel Organization)

Figure 3.2. Organization A: Parallel Structure

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no loops or cycles. In particular, consider the SA information shared between DM^1 and DM^2. The variables z^1 and z^{12} are generated as a result of DM^1's processing of x^1. Similarly, z^2 and z^{21} are produced by DM^2. Once DM^2 has forwarded x^{21} to DM^1, the final assessment $\bar{z}^1$ can be determined using the information fusion (IF) stage of DM^1. DM^2 determines his value of $\bar{z}^2$ after receiving z^{12}, z^{32} and after producing z^2. While precise timing is not explicitly required, it is implicit in that a particular stage of processing cannot be completed until all the requisite input variables are received. Furthermore, it is assumed that the overall input–output processing of the organization can be accomplished on the average within the mean interarrival time τ.

The second organizational structure, Organization B, incorporates a decisionmaker who has a supervisory role. It is defined as follows: the rectangular sector is divided into two equal subsectors for which DM^1 and DM^3 are responsible for assessing the threat; however, data from the area adjacent to the boundary betweem DM^1 and DM^3 are transmitted to the coordinator or supervisor, DM^2, who resolves conflicts and assigns targets either to DM^1 or to DM^3 as appropriate (Fig. 3.3). This is accomplished through command inputs v^{21} and v^{23} from the coordinator to the two commanders. They in turn exercise their response y^1 and y^3, respectively. Again, for computational simplicity, it is assumed that DM^1 and DM^3 have a single algorithm f^n, for their SA stage and two algorithms h_1^n and h_2^n for the RS stage. The coordinator, DM^2, has an algorithm IF^2 for processing the assessed situations z^{12} and z^{32} and two algorithms, h_1^2 and h_2^2, in the RS stage. The internal decision strategies are $p(v^1|\bar{z}^1)$, $p(v^2|\bar{z}^2)$, and $p(v^3|\bar{z}^3)$. The structure of this organization is shown in Figure 3.4. Again, note that the information structure is indeed acyclical.
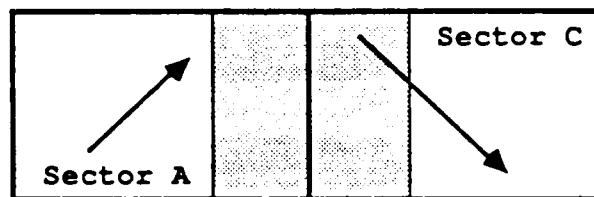
Figure 3.3. Two Sectors (Hierarchical Organization)

In order to avoid complex protocols, it is assumed that no more than one threat can be in each sector and there can be only one threat that crosses sectors at a time. These assumptions avoid two conflicts: (a) one DM having to decide about two threats at the same time and (b) the center DM receiving data from the other two DMs and having to assess two threats simultaneously. Actually, the second assumption can be relaxed so that two threats that cross boundaries can be present provided they do so on different boundaries and the net result is such that a single DM does not have to respond to both of them.
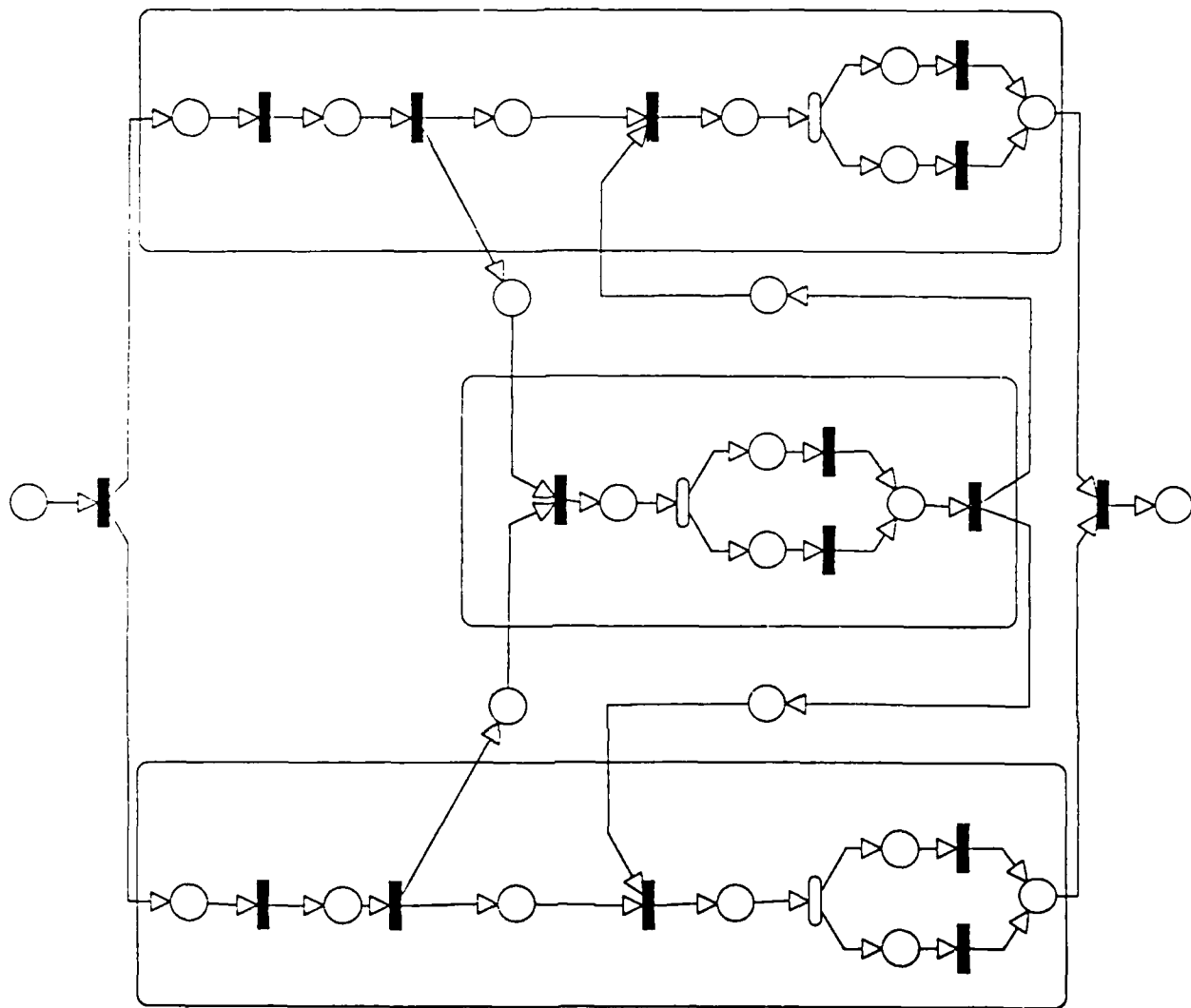
Figure 3.4. Organization B: Hierarchical Structure

Fourteen different threat configurations are possible. For the evaluation of the performance—workload locus, fifty six distinct threat sets were used where sets were distinguished by whether the threat was fast or slow and by what the direction of the threat was. The objective probability distribution p(x) was taken to be non-uniform. In order to provide some contrast and also represent a plausible situation, the probability distribution q(x) perceived by the three decisionmakers was based on the assumption that the DMs do not take into account that threats can cross sectors; they assign zero probability to such events. On the other hand, they assume a uniform probability distribution for the various configurations that do not include threats crossing sectors.

The level of activity, measured by whether a decisionmaker expects to respond to a threat or not is shown in Table 1. The active status denotes either autonomous operation —the DM receives a threat in his sector and responds to it -- ot interaction with another DM by sharing situation assessment information.

TABLE 1. Expected Activity by DMs for p(x) and q(x)

DM	STATUS	p(x)		q(x)	
		ORG A	ORG B	ORG A	ORG B
1	Active	64%	82%	50%	65%
	Inactive	36%	18%	50%	35%
2	Active	79%	50%	30%	30%
	Inactive	21%	50%	70%	70%
3	Active	64%	82%	50%	65%
	Inactive	36%	18%	50%	35%

3.6 RESULTS

The consistency measure Q for the parallel organization A and for task probability distributions p(x) and q(x) is shown in Figures 3.5 and 3.6, while Figures 3.7 and 3.8 are the corresponding plots for a hierarchical Organization B.

Figure 3.5 shows that there are no strategies that the organization members can use that will not lead to overload, if the interarrival time τ is less than 29 units of time. Furthermore, if τ is more than 43 units, then no strategy will overload the DMs. The fraction of strategies that satisfy the bounded rationality constraints is a non-decreasing function of τ, as shown by the gradual, step like increases in Q. Similarly, there are no strategies that will yield a cost that is less than 3.2 units, while if the constraint is that the cost be no more than 3.4 units, then all strategies are feasible. This is indicated in Figure 3.5 by the steepness of the slope in the $\bar{J}$ direction. Now consider Figure 3.6. This shows the effect of underestimating the task requirements by the decisionmakers. By neglecting to take into consideration the common occurence of threats that cross over from one sector to another and the resulting need for communication and coordination, the decisionmakers perceive that they can handle threats arriving every 14 units of time on the average. All strategies are feasible, if the threats arrive every 28 or more units of time. On that basis, they can choose strategies they believe to be feasible, but which in reality will cause overload and, consequently, a degradation of performance, possibly a severe one.
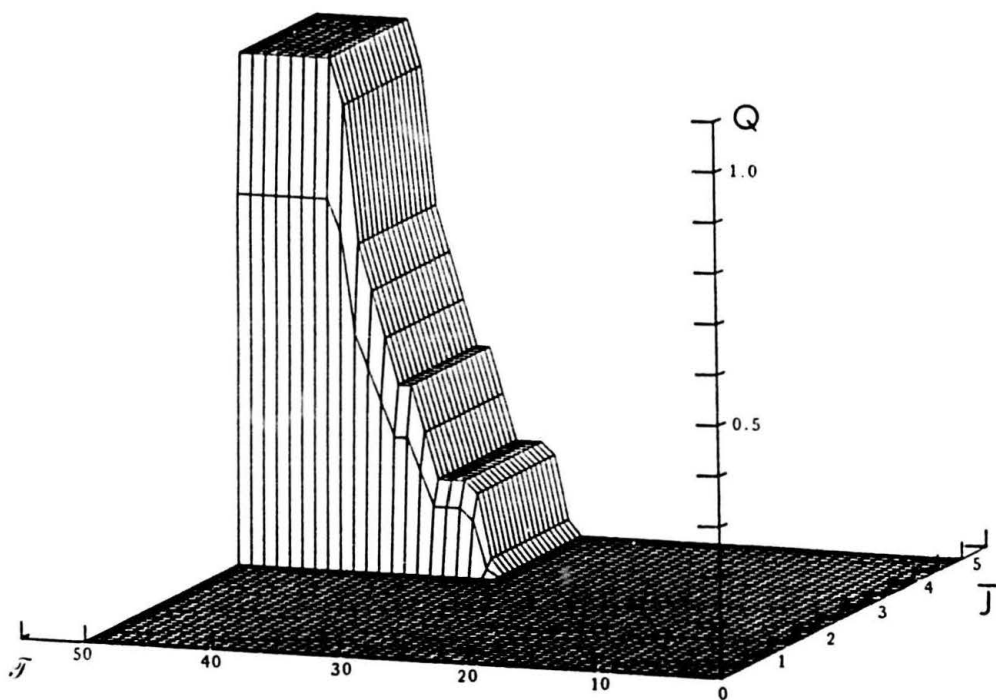
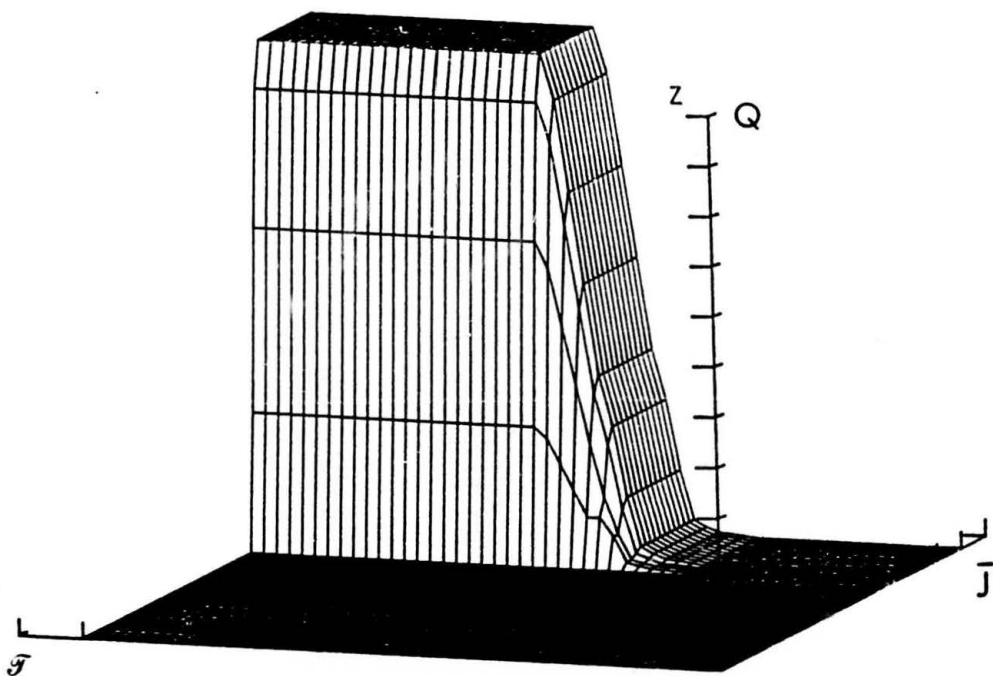Figure 3.5.   Consistency Measure Q for Organization A: p(x)

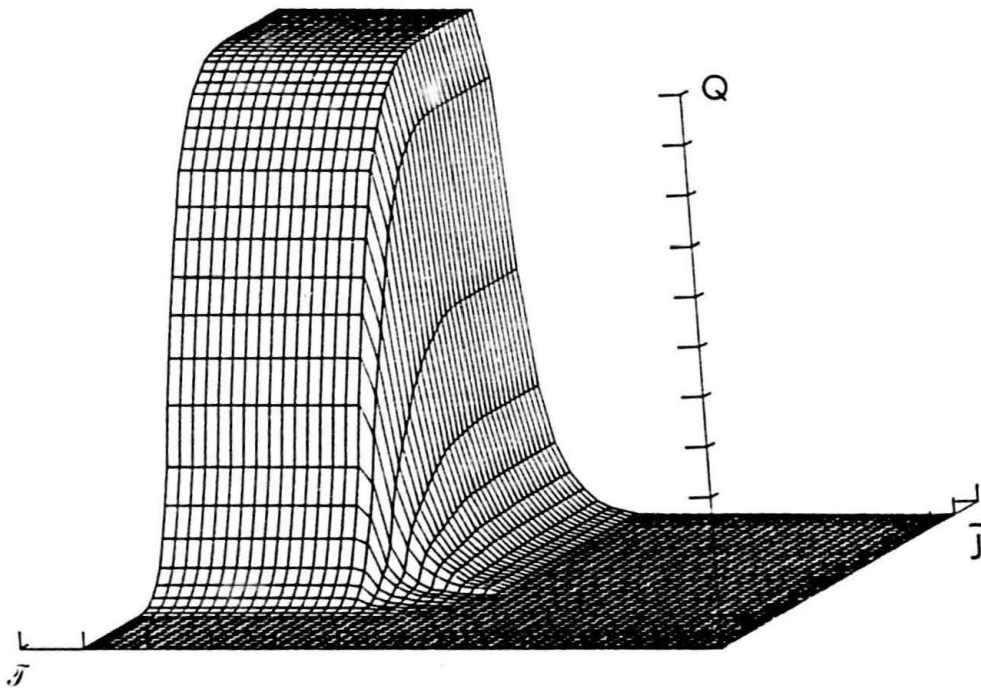Figure 3.6.   Consistency Measure Q for Organization A: q(x)

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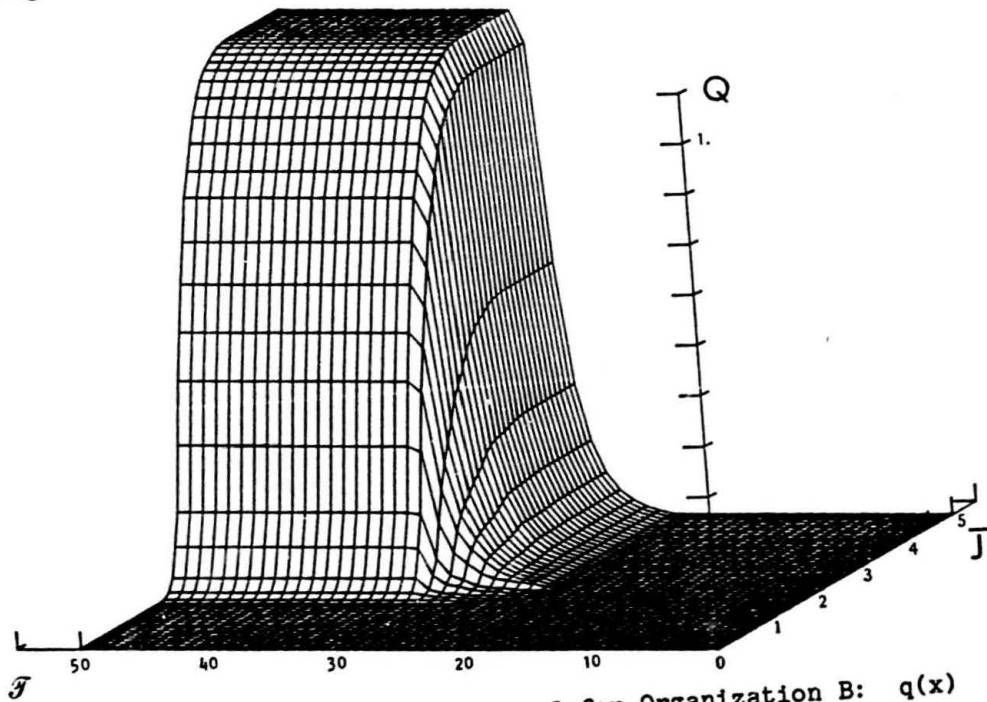Figure 3.7. Consistency Measure Q for Organization B: p(x)

Figure 3.8. Consistency Measure Q for Organization B: q(x)

Under this assumption, it is also clear that performance will degrade. Indeed, there are no strategies that will yield a cost of less than 3.5 units. Superposition of Figure 3.6 on Figure 3.5 shows clearly the effect of q(x). The DMs assume that the task is simpler than it really is and consequently, select inappropriate strategies that lead to high workload and degraded performance.

Very similar observations can be made by comparing the Q loci of Organization B, Figures 3.7 and 3.8. In that case, too, the Q locus for the objective probability is farther from the origin than the locus resulting when the perceived uncertainty by the decisionmakers is used. The decisionmakers have underestimated the need for coordination to handle threats that occur near or on the boundary between the two sectors.

The assumption that a decisionmaker may select any of the admissible, but no necessarily feasible, strategies with equal probability is not a realistic one. If the DM thinks that a certain subset Σ_s' of the decision strategy space Σ will meet the performance and workload constraints, then he will choose strategies from that set only and ignore the rest. This can be modeled by assuming a uniform probability distribution for the strategies in Σ_s' and assigning zero probability to the strategies not in Σ_s'. If a decisionmaker's perception of the task's probability distribution q(x) is such that Σ_s' is the null set, then a uniform probability distribution is assumed for selecting a strategy from the set Σ.

If the decisionmaker's q(x) is the same as the designer's, the objective probability distribution p(x), then the feasible strategy set is denoted by Σ_0'. The relative position, of the two strategy sets, the one due to q(x), Σ_s' and the one due to p(x), Σ_0', may be such that the two sets are disjoint, overlapping, or identically the same. Therefore, in selecting a strategy from Σ_s', the decisionmaker may be selecting a strategy that meets the specifications of the task as seen by the designer or he may not. In order to analyze the relationship between Σ_s' and Σ_0', the consistency measure introduced in Eq. (3.12) can be modified as follows:

$$\bar{Q}(\bar{J},\tau) = \begin{cases} V(\Sigma_0')/V(\Sigma) & \text{for } V(\Sigma_s') = 0 \\[2em] \dfrac{V(\Sigma_s') \quad V(\Sigma_0')}{V(\Sigma_s')} & \text{for } V(\Sigma_s') = 0 \\[2em] 1 & \text{for } V(\Sigma_0') = V(\Sigma) \end{cases} \qquad (3.15)$$

where $V(\cdot)$ is again the volume in the strategy space. The quantity $\bar{Q}$ can be interpreted as the probability that a decisionmaker, who perceives the probability distribution of the tasks are being q(x), will select a decision strategy that satisfies the requirements $(\bar{J},\tau)$.

3.7 CONCLUSION

In this chapter, an approach to the evaluation of alternative organizational designs has been presented. The issues that arise when the designer's and the decisionmakers' knowledge of the tasks and of their relative value differ have been discussed. A measure of organizational effectiveness has been introduced, the consistency measure Q, for the case when the designer and the decisionmakers differ in their perception of the uncertainty associated with the inputs or tasks. Two three-person organziations, one with parallel structure and one with a hierarchical one, have been used to illustrate the approach.

One weakness of the procedure is that the analytical formulation of the workload does not yield much insight to the differences between the two points of view. Alternatively, the computational approach yields results that are specific to each case and problem that are being studied. Thus, upon completion of this study, a major effort was initiated to develop efficient computational algorithms and implement them on a workstation so that many cases can be studied with ease. Such a workstation has now been developed and will be used for further studies and analyses.

4. MEASURES OF EFFECTIVENESS IN COMMAND AND CONTROL[*]

In the previous chapter, a methodology was presented for analyzing and comparing alternative organizational forms. In the language of the theories for system evaluation, two measures of performance (MOPs), accuracy and workload, were introduced and the MOP locus, the performance-workload locus, was defined. Then, a measure of effectiveness (MOE), the measure of consistency Q, was defined and evaluated on the basis of the MOP locus. These concepts are quite general and translate easily to the evaluation or assessment of C^3 systems. One of the tasks in the research effort was to approach the problem of evaluation from both sides – from the organization theory perspective and from the system design perspective. The long term objective has been to develop a unified approach.

In this chapter, a methodology for measuring the effectiveness of C^3 systems is described and is then applied to an abstraction of a C^3 system of the US Army.

4.1. INTRODUCTION

Improvements in weapon system technology, and higher capacity and speed in data transmission, combined with an increasing complexity of the battlefield, impose severe time constraints on hardware, software, and human decisionmakers. The purpose of this task was to extend the methodology presented in Bouthonnier and Levis [23] to consider measures of performance (MOPs) and measures of effectiveness (MOEs) that include time.

Time has always been of crucial importance in combat and, consequently, to command and control [24]. As Lawson [25] relates, "in a typical discussion of Command and Control, it is taken as axiomatic that the information presented to the commander must be 'timely' as well as accurate, complete, etc. Little or nothing is said about how timely is timely enough; nor is any yardstick given by which to measure 'timeliness'. Rather, the clear implication is that all would be well if only communications and computers were 'faster'. In addition, this attention to rates (e.g., information processing rates, rate of fire, etc.) in which time only appears in the denominator, has led to a preoccupation with the performance characteristics of the component parts of a C^3 system. It does not provide any means of comparing the effect of an increase in one 'rate' with that of an increase in some othe rate."

The methodological framework is the one developed by Bouthonnier and Levis [23]. The aspects that time can take in a warfare environment are numerous. The ones that this assessment methodology consideres are:

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[*]This chapter is based on the work of Phillipe H. Cothier [28].

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<u>System response time</u>. It characterizes the time delay between the moment when the C^3 system receives a stimulus and the moment it can deliver a response. It is the sum of all the time delays at every level of the process.

<u>Tempo of operations</u>. In most military situations, rates are used to express the important quantities, e.g., rounds per minute, miles per hour. The term in commom usage for the operating rate of a C^3 system is its "tempo". Lawson [25] defines it as the number of actions per unit of time which the system is executing and states, further, that "the tempo tells us how complex an environment the system can handle (i.e., its bandwidth) while the response time tells us when it responds in time (i.e., the phase delay in the system)".

These notions depend on what is actually taking place, i.e., the <u>scenario</u>. The event that stimulates the C^3 system is only the partial perception by the system of a global scenario. Different scenarios can be perceived through identical events, and the system is confronted with uncertainty. Once the scenario is identified with enough certainty, then an option must be selected. It appears that any assessment of a C^3 system must consider the crucial role of the scenario and the tempo of operations it implies: to each scenario corresponds an evaluation of the effectiveness of the system. These partial evaluations can be merged into an overall measure of effectiveness for a given range of possible scenarios.

<u>Timeliness</u> is defined here as a system's ability to respond within an allotted time. <u>Allotted time</u>, in this context, is the time interval over which our forces, which include a C^3 system being assessed, can affect the environment. This allotted time is described by a <u>window of opportunity</u> whose parameters are determined by the system and the mission. Two quantities are needed to specify the window of opportunity: one choice is the lower and the upper bound of the time interval, t^* and t^{**}, respectively; another one is one of the bounds and the length of the interval, e.g., t^{**} and Δt. Such a time interval is not sufficient to yield by itself a measure of effectiveness; one must also consider the way this time is employed, i.e., one must consider the doctrine that is in effect, was well as the tactics that are feasible in such an interval.

The methodology used in this paper is based on six concepts: system, environment, context, parameters, measures of performance, and measures of effectiveness. The first three are used to pose the problem, while the last three define the key quantities in the analytical formulation of the problem. The analytical aspects of the methodology address mainly the relationships between hardware characteristics, system structure, and standard operating procedures (SOPs) to system performance.

The <u>system</u> consists of components, their interconnections, and a set of operating procedures. A boundary can be drawn that defines what is included within the system whose effectiveness is to be assessed. What is included depends on the analysis at hand. The <u>environment</u> consists of our own forces and the adversary's forces upon which our forces can act and which can act upon ours. For example, the C^3 system is used to direct forces and monitor

(sense) the environment. An engagement between two forces in an urban area or at a mountain pass define typical environments. A C^3 subsystem of a fire support system or a communication network are typical systems. The context denotes the set of conditions and assumptions within which the system and the environment exist. The relationship between system, environment, and context are shown in Figure 4.1.
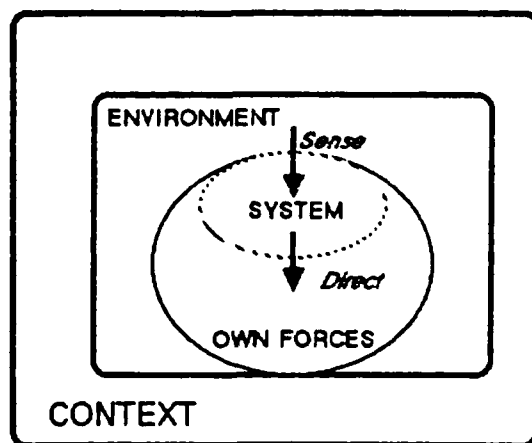

Figure 4.1. System, Environment and Context

Parameters are the independent quantities used to specify the system and the mission requirements. For example, in the case of a fire support system, system parameters may include quantities that describe the detection equipment, computational time delays, kill radius of the munition, and failure probabilities associated with the components, to name but a few. Parameters of the mission may be the tempo of operations, as described by the speed of the threats, and the size of the engagement.

Measures of Performance are quantities that describe system properties or mission requirements. MOPs for a command and control system may include reliability, survivability, cost, and probability to kill. The mission requirements should be expressed by the same quantities as the system MOPs, e.g., minimum reliability or survivability, maximum cost, or minimum probability to kill. System parameters are defined within the system boundary; MOPs may be defined within the boundary or they may include aspects of the environment.

Measures of Effectiveness (MOEs) are quantities that result from the comparison of the system MOPs to the mission requirements. They reflect the extent to which the system meets the requirements. To evaluate the MOEs, it is necessary to go outside the boundary and consider the environment. Only then could the effect of the system on the mission outcome be evaluated. These definitions of parameters, MOPs, and MOEs are consistent with those developed at a recent MORS Workshop on the subject [26].

In this methodology for assessing effectiveness, the system MOPs and mission requirements must be modeled and analyzed independently, but in a common context. The system capabilities should be determined independently of the mission requirements, and the mission requirements should be derived without considering the system to be assessed. Otherwise, the assessment is biased. Since the steps of the methodology have been presented in [23], they and the modeling of timeliness will be described here through application to an idealized tactical fire direction system. This problem is formulated in Section 4.2; in Section 4.3, the system and the mission are modeled and their respective loci defined. In Section 4.4, a class of measures of effectiveness is defined, while in Section 4.5 the results are presented and discussed.

4.2 SYSTEM AND MISSION

The concepts discussed in Section 4.1 can be illustrated by applying the methodology for System Effectiveness Analysis to an "electronically integrated command and control information system that also processes fire missions" [27].

One can isolate three main elements in a fire support system at the battalion level: the forward observer, the battalion fire direction center, and the field artillery cannon battery. The system can include several forward observers and several batteries connected to the same central battalion computer.

The Forward Observer (FO) receives the initial stimulus by detecting an enemy threat. The FO is equipped with vehicle position determining equipment and a laser rangefinder. These allow the FO to locate accurately area targets for fire and to conduct one-round adjustments. The FO is also equipped with the Digital Message Device (DMD), a portable, battery-powered device that transmits and receives digital bursts. The FO uses the DMD to communicate estimates of the position and velocity of the target, and requests for fire to the battalion computer.

The battalion Fire Direction Center (BN FDC) is provided with a central computer. Digital communication over any standard communication means (radio or wire) provides for input of data into the computer center and for the return of the results. Forward observers and firing batteries are provided with remote terminal equipment to obtain data from the central computer.

The Battery Display Unit (BDU) is the cannon battery's link with the C^3 system. Each battery has one BDU. The BDU assists execution of fire plans by receiving and printing firing data for each target that the battery will fire. This receive-only unit initiates an automatic acknowledgement that is sent back to the FDC computer.

While this is the basic configuration, additional equipment is maintained in parallel to augment the basic system. Voice communication links can be added in parallel with the digital links, for instance, between the battalion fire direction center and the cannon battery. Voice communication is slower, more vulnerable, but still very useful, if the digital link fails. If the

fire support system computer fails at the battalion level, the battery has the capacity to do the firing computations locally. This alternative is slower, though.

A schematic representation of the system that will be analyzed is shown in Figure 4.2. Seven stages are shown. In this model, nodes are not subject to failure; only links are. Alternative implementations of each stage are shown by parallel links; e.g., a voice link is in parallel with the digital link between the battalion fire direction center and battery B.
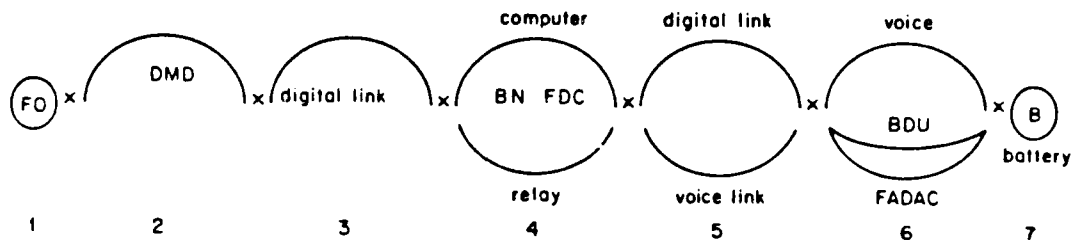

Figure 4.2. Fire Support System Structure

If the BN FDC computer does not work, the target estimates from the FO can be sent to battery B through voice communication (the BN FDC acts as a simple relay). The battery crew can then compute the firing data manually with the Field Artillery Digital Automatic Computer (FADAC). In the case where the firing data are computed at the BN FDC level and transmitted by voice communication to battery B, neither the BDU nor the manual technique have to be used. The voice communication of the firing data reaches directly the firing platform of the battery. In order to assess properly the effectiveness of this system, it is necessary to specify the environment and context in which it operates, i.e., define the scenario.

The idealized scenario that will be considered is shown in Figure 4.3. Some vital node of our forces' C^3 system is situated at the end of a valley. A road along this valley leads to this node. The topography of the area is perfectly known by our forces, and the road is the only access to the node. A fire support battalion including one forward observer (FO), one battalion fire direction center (BN FDC), and two batteries B_1 and B_2 has been positioned to protect this access. This battalion is equipped with the fire support system defined in Figure 4.2. The batteries cannot see the road: they shoot according to the firing directions that are computed on the basis of the observer's estimates.

An enemy tank (threat) appears in the field of vision of the forward observer. It is moving on the road towards our forces with hostile intentions. The mission is to defend the node, i.e., to prevent the tank from attacking the node.
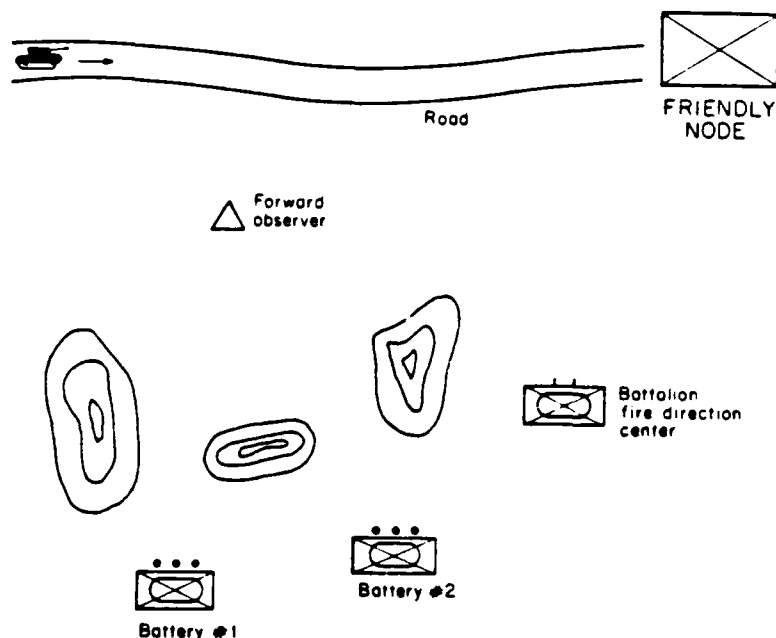
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Figure 4.3. Scenario

It is assumed that the threat cannot attack the fire support battalion directly; the only countermeasure that will be considered is the jamming of communications by the enemy. It is also assumed that the threat will pursue its attack, even after it is fired upon. It will try to carry out its own offensive mission, as if it encountered no reaction from our forces. This is a highly idealized situation. It is used to illustrate the methodology, rather than represent current practice in terms of doctrine or tactics.

The problem of interest is to determine how effective this particular command and control system is. But, as indicated earlier, to assess effectiveness, one has to go outside the boundaries of the C^3 system itself and consider the mission and the environment. In this case, it is postulated that the system to be assessed consists of the forward observer, the BN FDC, the BDU, the FADAC, and the associated communication links. The batteries themselves, as well as the threat and the node to be defended, constitute the environment; the terrain constitutes the context. Note that in applying this

methodology, a choice has to be made each time as to what is included within the boundaries of the system. In this case, the sensors are included, as are some parts of the weapons system. In another application, the whole fire support system could be considered as a integrated weapons system.

The system's performance will be characterized by three MOPs. Two of them define the window of opportunity, namely, the upper bound t^{**} and the width of the window Δt. The third one is the overall probability of kill (OPK) that measures the ability of the total fire support system to stop the threat.

For each value of the selected system parameters, a value for the triplet $(t^{**}, \Delta t, OPK)$ is obtained. As the parameters are allowed to vary over their respective range of values, a locus is constructed in the space of MOPs. This is defined as the system locus, L_s.

The mission requirements in this case are expressed simply as the minimum acceptable probability that the node will be defended successfully, i.e., that the threat will be prevented from firing at the node. This requirement can also be expressed as a locus in the MOP space; it is the mission locus L_r. Effectiveness for this system and mission is defined by how well the overall kill probability meets the mission requirement.

In the next section, the mathematical models of the system and the mission will be developed and the corresponding loci constructed.

4.3 SYSTEM AND MISSION MODELS

Each node and each link of the C^3 system is assumed to have a probability of failure, independently of the countermeasures taken by the enemy. These component failure probabilities determine the system's reliability. Since the system is operating in a hostile environment, the communication links are subject to jamming by the enemy. The probability of failure due to jamming determine the system's survivability. Although the two concepts of reliability and survivability are distinct because the underlying probabilities of failure have different causes, in this analysis they will be merged to reduce the dimensionality of the problem. A single vector of probabilities, p, will be used as a parameter that describes the failure characteristics of the system's components. In a full scale analysis, the two will be separate.

The parameter that determines the tempo of operations is, in this case, the speed w of the threat. A whole range of different versions of the scenario can be investigated by varying the speed w.

It is assumed that the main source of uncertainty is the estimate of the threat's state by the forward observer. If the FO uses two sightings to determine the threat's state, then an appropriate system parameter can be, for example, the angle β that separates the two sightings. Intuitively, the larger the angle β the more accurate the speed estimate, but the longer the response time.

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Since the commander has a choice as to the resources he may use, two cases will be considered: (a) one battery (B_1), and (b) two batteries (B_1 and B_2). In the second case, two different tactics can be analyzed: coordinated fire and uncoordinated fire.

Response Time and Window of Opportunity

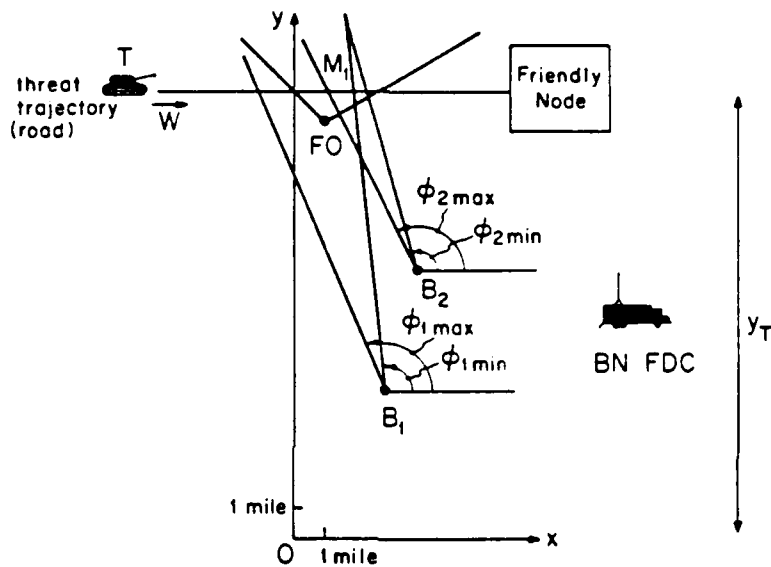The geometric relations for this scenario are shown in Figure 4.4.

Figure 4.4. Geometric Relations between System and Threat

To begin the process of quantifying the timeliness characteristics of the system through the determination of the window of opportunity, consider Figure 4.5, which shows the chronological sequence of the response process. The time that a round fired by a battery hits the ground, t_{impact}, is given by:

$$t_{impact} = t_{obs} + \sum_{i=1}^{3} \Delta\tau_i \tag{4.1}$$

$\Delta\tau_i$ is computed from the geometry in Figure 4.4. It is a function of the speed w, the angle β, and the observation time [28].

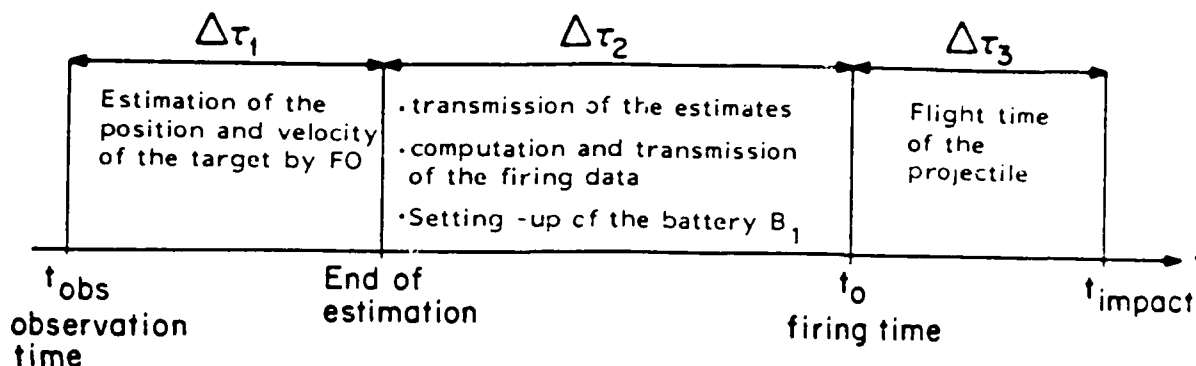$$\Delta\tau_1 = \Delta\tau_1(w, \beta, t_{obs}) \tag{4.2}$$

Figure 4.5. Time Profile of the System Response

A sensitivity analysis has shown that $\Delta\tau_3$ can be taken as constant for this geometry and characteristics of the weapon system. For the values chosen for this example, this constant is 36 seconds.

Let the lower bound of the window of opportunity, t^*, be equal to the minimum impact time. For a given angle β and a given target velocity w, the earliest impact time is determined by the earliest possible observation time, i.e., $t_{obs} = 0$, and by the minimal time delay $(\Delta\tau_2)_{min}$ between the end of the estimation and the actual firing of the battery. Thus:

$$t^* = \Delta\tau_1(w,\beta,0) + (\Delta\tau_2)_{min} + \Delta\tau_3 \tag{4.3}$$

This earliest impact time may be considered as the response time of the system. Note that it depends on the scenario, the sensor characteristics, and the positioning of the forward observer and the batteries with respect to the threat.

Let M_1 be the point on the trajectory where the threat leaves the area covered by battery B_1 (see Fig. 4.4) in the single battery case, or the area covered by either battery in the two battery case. Let the upper bound of the window of opportunity, t^{**}, be the time that the threat moves past point M_1. This bounds from above the admissible impact times, i.e., only impact times occuring within the window of opportunity are allowed:

$$(t_{impact})_{max} \leq t^{**} \tag{4.4}$$

where

$$t^{**} = K/w \tag{4.5}$$

and K is the distance to point M_1 and depends on the geometry of the situation.

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The resulting time interval, Δt, is the system window of opportunity: the system can deliver a response to the stimulus at any time t_{impact} between t^* and t^{**} (for $t^* < t^{**}$). The window of opportunity is completely characterized by the ordered pair $(t^{**}, \Delta t)$, where $\Delta t = t^{**} - t^*$. Changes in the values of the parameters w, and β lead to changes in the window of opportunity.

Performance

The single shot kill probability SSPK associated with an impact time is easily computed by taking into account the uncertainty in the speed estimate, and the kill radius of the munition. For fixed values of w and t_{obs}, the shape of the variations of SSPK with t is given in Figure 4.6; the latter also shows an important trade-off. As β increases, the width of the window of opportunity decreases because it takes a longer time for the FO to obtain his estimate. But at the same time, a large β yields a more accurate estimate of the speed of the target. Therefore, the kill probability is increased. The upper limit t^{**} is unaffected by changes in β.
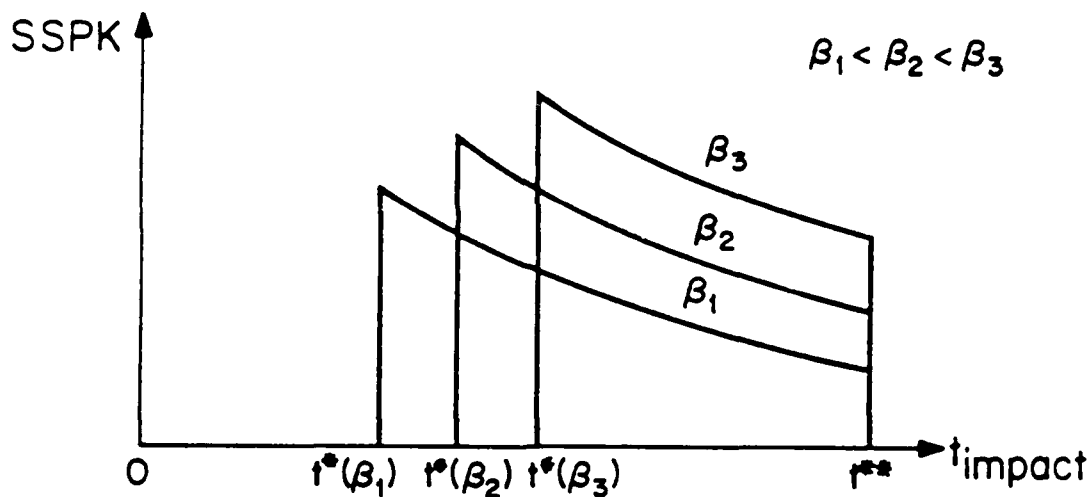
Figure 4.6. Single Shot Kill Probability as a Function of Impact Time

Also, as time goes by, if there are no updates of the threat's state, the uncertainty of its exact position increases and, therefore, SSPK decreases with time.

The seven-stage structure of the C^3 system has been presented in Figure 4.2. The corresponding tree that represents the system states, Figure 4.7, reveals that out of the ten possible paths, six paths do not lead to the transmission of information from the forward observer to the batteries. For each of the four paths that indicate successful communication, the following quantities are defined:

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$q(i)$: probability that the path #i is operational; $i = 1,2,3,4$.

$\gamma(i) = (\Delta t_2)_{min}(i) + \Delta t_3$, i.e., $\gamma(i)$ is the minimum time delay between the estimates by the FO and the impact time.

$\delta(i)$: minimum time delay necessary to recompute new firing data based on the initial estimates, to transmit them and to set up the battery accordingly. If the system recomputes the firing data immediately after each shot and fires in sequence, then $\delta(i)$ represents the minimum time delay between two shots.
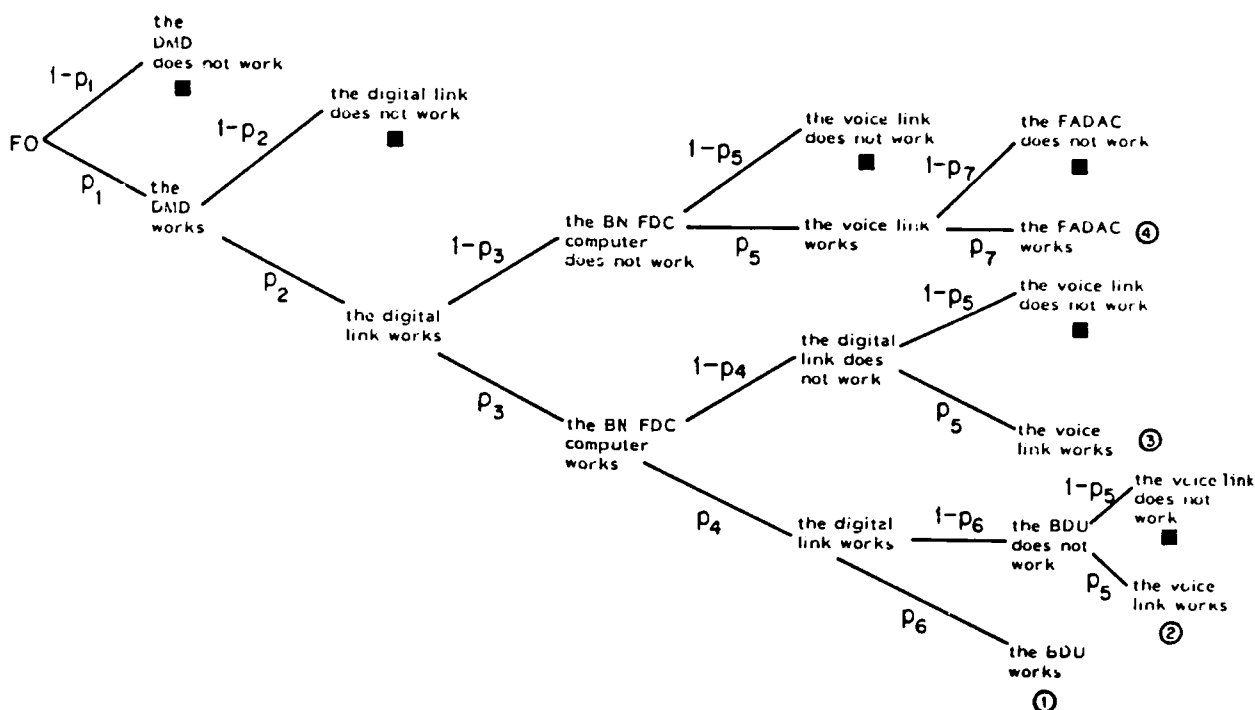
Figure 4.7. Tree Representing System's Operational States

The earliest response time to the stimulus is t^*. The system can use the remaining time within the window of opportunity to deliver other responses, e.g., to fire again, therefore increasing the overall kill probability. This can be done in many different ways. This analysis focuses on two of them, which are classical military doctrines, known as "LOOK-SHOOT-SHOOT-SHOOT..."[LSS] and "LOOK-SHOOT-LOOK-SHOOT..."[LSLS].

Doctrine 1: "LOOK-SHOOT-SHOOT-SHOOT..." The observer initially makes estimates of the speed and position of the threat, and then the battery keeps on shooting at the target, recomputing each new firing data on the basis of these initial estimates.

The observation time t_{obs} is the same for each shot, since there is no updating of the estimates. The time delay between two shots is thus the interval δ. The battery fires as many shots as possible within the window of opportunity, since there is no feedback from the observer.

Doctrine 2: "LOOK-SHOOT-LOOK-SHOOT..." After each shot, if the threat is neither destroyed nor incapacitated, the observer makes new estimates of its speed and position, new firing data are computed on the basis of these updated estimates, the battery (or batteries) shoots according to these new firing data, and so on until the upper limit of the window of opportunity is reached.

The overall probability of kill (OPK) can be computed from the single shot probability of kill, as follows:

$$OPK = 1 - \sum_{n=1}^{n^*} SSPK(t_{impact\#n}) \qquad (4.6)$$

where n^* is the number of shots possible for a given doctrine and a given window of opportunity. The single shot probability is given by:

$$SSPK(t_{impact\#n}) = \frac{\xi(w,\beta,t_{obs\#n})}{t_{impact\#n} - t_{obs\#n}} \qquad (4.7)$$

where the function ξ depends on the kill radius of the munition, the speed of the target, and the accuracy of the observation. Similar expressions have been derived for Doctrine 2 as well as for the two battery case with coordinated and uncoordinated fire. For details, see Cothier [28].

In calculating OPK, it is assumed that the C^3 system operates in the same mode (i.e., the same path is used) throughout that engagement. Therefore, four different values of OPK can be computed, one for each possible path.

4.4 SYSTEM AND MISSION LOCI

The three system MOPs (t^{**}, Δt, OPK) can be derived for each path i. However, it is preferable to obtain an overall probabilistic description of these MOPs. For any of the 6 paths (Fig. 4.7) that fail to transmit the information from the FO to the batteries, Δt is zero, and so is the OPK.

For paths #1 to #4, Δt_i and OPK_i vary according to what doctrine is chosen. The MOPs to consider are thus the expected values of these quantities.

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$$\Delta t = E\{\Delta t_i\} = \sum_{i=1}^{4} q(i) \cdot \Delta t_i \qquad (4.8)$$

$$OPK = E\{OPK_i\} = \sum_{i=1}^{4} q(i) \cdot OPK_i \qquad (4.9)$$

where $q(i)$ is the probability that the i-th path is used. The values of $q(i)$ is obtained by using structure functions and the failure probabilities (Cothier [28]). From now on, only the expected values of Δt and OPK will be considered.

The dependence of the system MOPs on the system parameters is shown in Figure 4.8. Note that OPK depends directly on the parameters w, β, and p, on the two other MOPs, t^{**} and Δt (i.e., the window of opportunity), and on the doctrine used. In other words, the parameters are mapped twice in the third MOP, directly and indirectly.
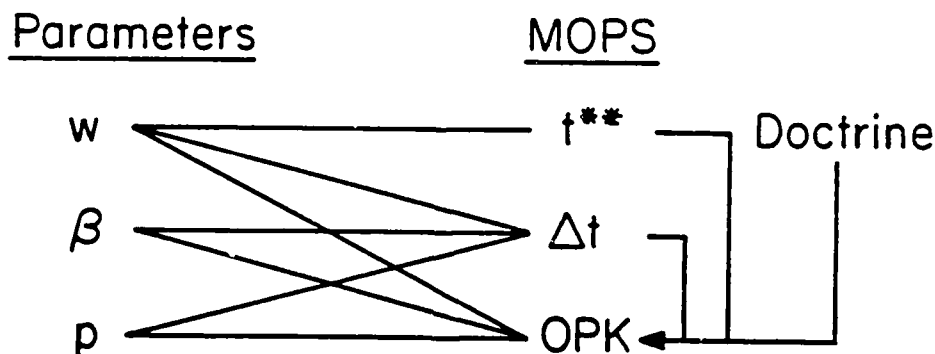
Figure 4.8. Mapping of the System Parameters into the System MOPs

To each value of the parameter set (w,β,p) corresponds a point in the MOP space (t^{**}, Δt, OPK). Now consider all the allowable values that the parameters make take:

$$w_{min} \leq w \leq w_{max}$$

$$\beta_{min} \leq \beta \leq \beta_{max} \qquad (4.10)$$

$$p_{min} \leq p \leq p_{max}$$

If the parameters are allowed to vary over their admissible ranges, then the variations define a locus in the MOP space. This is the system locus L_s.

Mission Locus

The analysis of the mission in this case is quite simple: the mission requirements can be expressed directly at the MOP level. The mission objective reduces to a single requirement, a condition on the third attribute OPK. If λ is the minimum probability that the threat will not be able to attack the node being defended, then the mission locus, L_r, is the region in the MOP space (t^{**}, Δt, OPK) that satisfies the inequality:

$$\lambda \leq OPK \leq 1 \tag{4.11}$$

In general, this would not be the case. Substantial analysis would be required to convert mission objectives into requirements and then express the latter as a locus in the MOP space.

In this section the system locus and the mission locus have been derived. The timeliness of the system has been described in terms of the window of opportunity, which, together with the performance measure OPK, have led to the system locus. In the next section, the two loci will be used to define and evaluate MOEs.

4.5. MEASURES OF EFFECTIVENESS

The next step consists of comparing quantitatively the system MOPs to the mission requirements, using the geometric relationship between the two loci, L_s and L_r, in the MOP space. If the two loci do not overlap, i.e., if

$$L_s \cap L_r = \phi \tag{4.12}$$

then the system MOPs do not satisfy the mission requirements for any operating state of the system. Consequently, effectiveness should be zero, regardless of which measure is used. On the other hand, if the two loci coincide, i.e., if

$$L_s \cap L_r = L_s = L_r \tag{4.13}$$

then the system and the mission are perfectly matched, and effectiveness should be equal to one. Three cases can be distinguished when the two loci have points in common.

(a) Neither locus is included in the other,

$$L_s \cap L_r \neq \phi \text{ and } L_s \cap L_r < L_s \text{ and } L_s \cap L_r < L_r \qquad (4.14)$$

In this case, only some of the values that the system MOPs may take satisfy the mission requirements. Many different measures can be used to described the extent to which the system meets the requirements. Each of these measures can be considered as an MOE which, if normalized, takes values in the open interval (0,1). Let V be such a measure. Then one MOE is defined by

$$E_1 = V(L_s \cap L_r)/V(L_s) \qquad (4.15)$$

while another is

$$E_2 = V(L_s \cap L_r)/V(L_r) \qquad (4.16)$$

(b) The system locus is included in the mission locus:

$$L_s \cap L_r = L_s \qquad (4.17)$$

The measure E_1 is equal to unity — all operating conditions of the system meet the requirements. But E_2 is less than one; the system can attain only certain values of the requirements.

(c) The mission locus is included in the system locus:

$$L_s \cap L_r = L_r \qquad (4.18)$$

that is, the system meets all the requirements, but also has operating conditions that do not meet the requirements. Then E_1 is less than one, and E_2 is equal to unity.

These measures are only two of the many that can be defined; they can be thought as partial MOEs, since they give only partial information about the relationship between the two loci. These partial measures can be combined into a single measure through the use of a utility function:

$$E = u(E_1, E_2, \ldots, E_k) \qquad (4.19)$$

The subjective judgements of the system developers and the users can be incorporated into the effectiveness analysis through the selection of the partial measures and the utility function.

4.6 EFFECTIVENESS ANALYSIS AND COMPARISON OF DOCTRINES

For this example, only the first partial MOE of Eq. (4.15), E_1, will be used. The mission locus is such that E_2 is very small and does not discriminate between different cases.

The One-Battery Case: Comparison of Two Doctrines

Figures 4.9 and 4.10 show the system locus and its intersection (shaded region) with the mission locus for each doctrine. The ratio of the shaded volume over the total volume of the system locus is larger for doctrine 1 and for doctrine 2:

$$E_1(1 \text{ battery, doctrine } 1) = 0.55$$

$$E_1(1 \text{ battery, doctrine } 2) = 0.50$$

When the tempo of operations is fast (the threat moves rapidly), the window of opportunity is small: it is better to make an accurate measurement of its speed once and then fire rapidly in sequence without taking time to make new estimates, rather than to make an estimate, shoot, make a new measurement, and so on. Therefore, the LSS doctrine is more effective than the LSLS doctrine. The first doctrine provides a more timely response — while the initial response time of both doctrines is the same, doctrine 1 allows for a higher rate of firing than doctrine 2.

The Two Battery Case

When the two batteries B_1 and B_2 are considered, it appears from Fig. 4.4 that their areas of coverage overlap. The threat moves first on a part of the road that is covered by battery B_1, then on a part that is covered by both B_1 and B_2, and then on the part that is covered by B_2 alone. It has been assumed that the tank has to go beyond the range of B_2 in order to be able to fire at the C^3 node. Therefore, the probability of kill varies with time, suddenly increasing, then decreasing. Assuming a "LOOK-SHOOT-SHOOT-SHOOT..." doctrine, two different options for the fire support commander will be considered:

Option 1: The two batteries shoot at the threat independently, each one using its window of opportunity at the maximum. There is no coordination between the two batteries.

Option 2: Battery B_1 starts firing only when the threat enters the area covered by both batteries. In other words, the commander decides not to fire immediately with B_1, but to wait until coordinated fire can be achieved, i.e., both batteries B_1 and B_2 shooting so that their projectiles hit the target trajectory at the same time. The system's window of opportunity is thus reduced to that of battery B_2. The time interval during which B_1 holds its fire can be used to keep the observer's estimate updated.
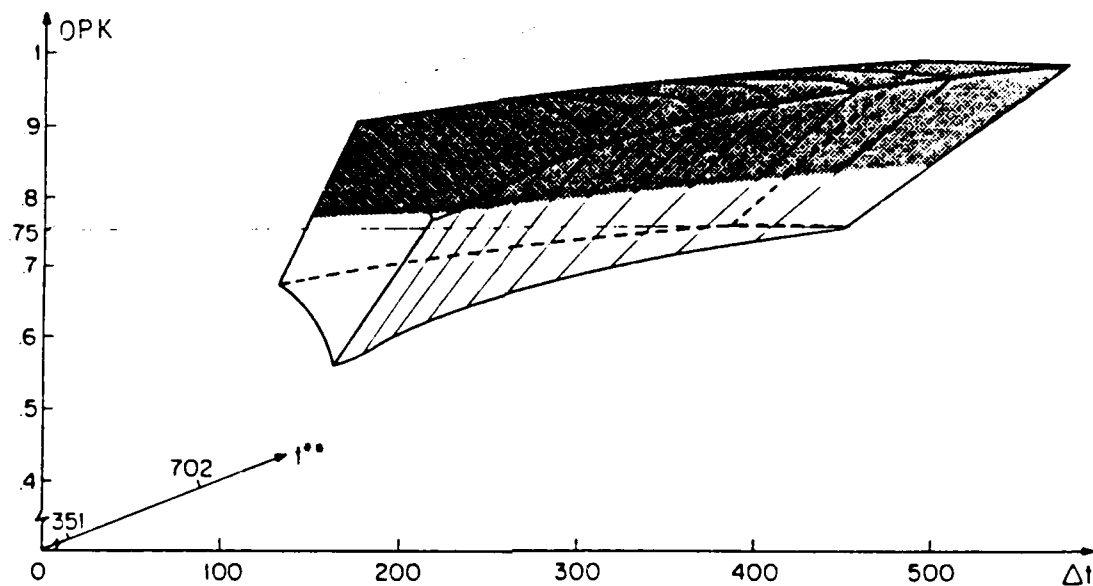
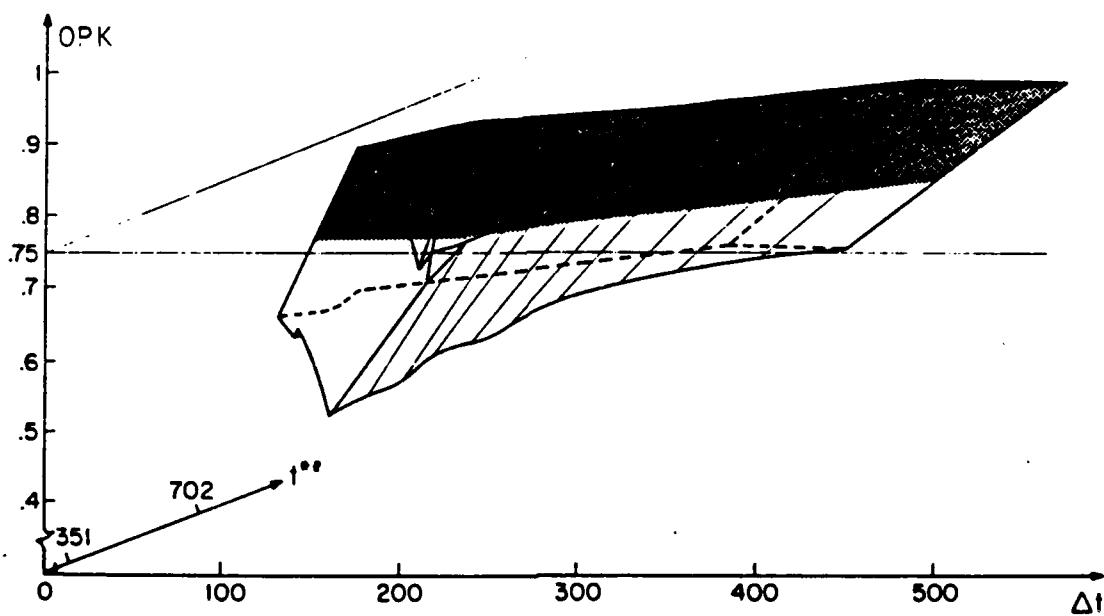Figure 4.9. Doctrine 1 (LSSS) System and Mission Loci

Figure 4.10. Doctrine 2 (LSLS) System and Mission Loci

Figure 4.11 and 4.12 show the system locus and its intersection (shaded region) with the mission locus for both Options 1 and 2. The evaluation of the effectiveness of the system for both options, measured by the ratio of the shaded volume over the total volume of the system locus, yields the following results. Let $E_1(1)$ be the MOE when Option 1 is used and $E_1(2)$ when Option 2 is used.

Then

$$E_1(1) \cong E_1(2) \cong 0.6$$

Therefore, both options result in approximately the same value for the effectiveness of the system. In Option 2, fewer shots are fired than in Option 1. In this case, coordination reduces costs for the same kill probability. However, this is not reflected in the MOE. Additional MOPs, such as cost, must be introduced, if one would like to discriminate between the two options.

It is important to note that Option 2, coordinated fire, is a better choice than Option 1, although its window of opportunity is much narrower. In fact, the time available is better managed: it is more effective to wait in order to implement a better option. This example shows that a larger size of the window of opportunity does not necessarily lead to higher effectiveness.
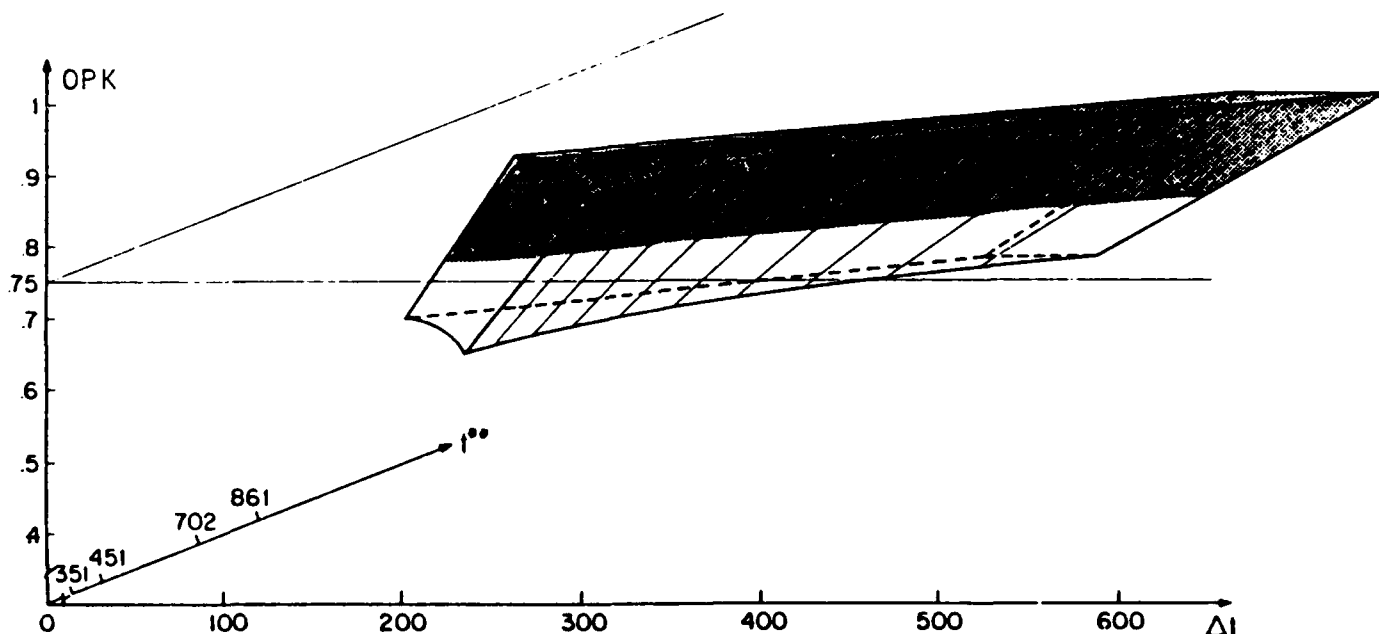

Figure 4.11   Option 1 (immediate fire without coordination)
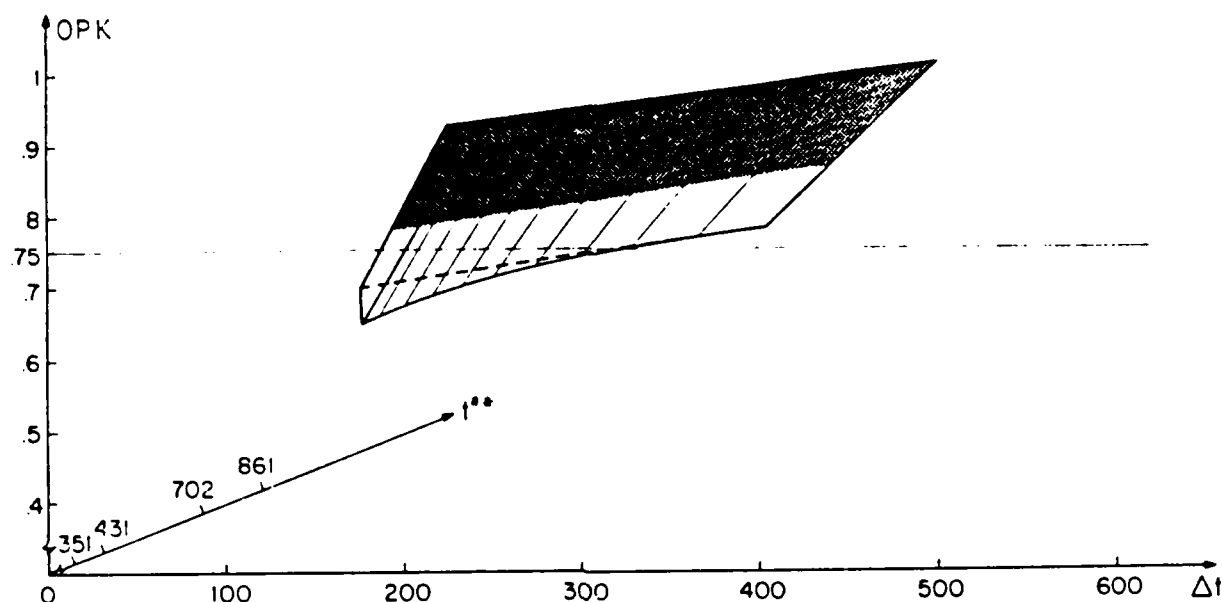System and Mission Loci

Figure 4.12. Option 2 (wait and coordinate) System and Mission Loci

4.7 CONCLUSIONS

In this chapter, the notion of timeliness has been integrated in the analysis of a system's effectiveness by treating the temporal characteristics of the system as performance measures. The resulting measures of effectiveness have embedded in them the time-related notions of response time and tempo of operations through their impact on the window of opportunity. These MOEs allow also the quantitative comparison of different doctrines: Some doctrines are shown to make better use of the available time than others. Therefore, this methodology for effectiveness analysis can be used to evaluate doctrines appropriate to a given situation.

A second point has been illustrated by considering the relationship between system components. While the speed of processing and transmission of data can be improved, the effectiveness of the system may not change if, for instance, the reliability and survivability of the system's components are not improved also. Faster does not necessarily mean better; it can even mean worse, if the increase in speed is gained at the expenses of the system's survivability. The methodology allows one to relate a change in one part of the system to a change in another part: the variations in the features of a given system are not considered separately, but jointly. This yields useful perspectives for the design of future C^3 systems. The influence of any modification either in the components, or the structure, or the doctrine, can be evaluated, using the proposed measures of effectiveness of the system.

A third point refers to the window of opportunity. The size of the window of opportunity is not a sufficient determinant of a system's timeliness. The location of the window, determined by the response time, must also be considered.

The methodology is flexible enough to be adapted to many kinds of systems: evolving systems [29], automotive [30], or manufacturing [31. Current efforts are directed toward developing the properties of several classes of MOEs, developing graphics software for the efficient construction and analysis of the system and mission loci, and applying the methodology to more complex problems such as evaluating the effectiveness of a large C^3 system for doing indirect identification of friend, foe, or neutral.

5. CONCLUSIONS

The goals of the research reported in this document were: (a) the further development of a quantitative methodology for the design analysis, and evaluation of command and control organizations, and (b) the development of a methodology for the assessment of C^3 systems that is consistent with the methodology for the evaluation of the decisionmaking organizations these systems support.

5.1 ORGANIZATIONS

The specific objective designed to meet the first goal was the consideration of the effect that different subjective probabilities and perceptions of the value of the tasks by individual decisionmakers can have on the organization's performance. The original approach included the development of the counterparts to N-dimensional information theory and the Partition Law of Information when weighted entropy is used in the place of classical entropy. While this development was carried out, the formal results did not yield any insight into the research questions. The resulting expressions were too complicated to be amenable to a physical interpretation. Consequently, the research effort was redirected toward using the conventional formulation of the Partition Law of Information, but complementing these results with efficient computational procedures for the study of the phenomena of interest.

The problem of qualitative differences in the tasks of an organziation has been approached by distinguishing four cases:

Case 1: The organization designer assumes that the decisionmakers know the objective probabilities of the tasks to be performed and all tasks are of equal importance. In this case, the weighting coefficients in the entropy expressions and in the objective function are unity. This is the base case that has been analyzed fully in earlier work.

Case 2: The organization designer considers that the decisionmakers do not know the correct probability distribution for the various tasks. In this case, weighted entropy is used to estimate workload, but the objective function has unity weighting coefficients, as in Case 1.

Case 3: The designer assumes that the decisionmakers do know the actual task probabilities, but have a different perception of the relative importance of tasks. In this case, the computation of workload is as in Case 1, but the objective function is different.

Case 4: This is the most general case. The designer assumes that the decisionmakers do not know the actual task probabilities and give different relative weights to the various tasks. This case subsumes the other three cases.

Detailed analytical results for the difference in workload under the correct probability distribution and the perceived ones were obtained for the interacting decisionmaker with bounded rationality. The expressions for the individual components of workload, i.e., throughput, blockage, coordination, and noise were also obtained. However, the complexity of the resulting expressions made it difficult to obtain general results. Therefore, a previously developed algorithm for three member organizations was modified and expanded to handle cases, 2, 3, and 4. Computational results for two alternative three person organizations were obtained using a new implementation of the algorithm. This implementation was on an IBM PC/AT and uses graphics extensively.

In order to evaluate the effect that differences in the perception of task uncertainty (Case 2) have on organizational performance, a consistency measure was introduced. This measures the effect of selecting strategies from a perceived feasible strategy space as opposed to selecting one from the actual feasible strategy space.

5.2 MEASURES OF EFFECTIVENESS

The basis for the analysis and evaluation of alternative organizational designs was the performance-workload locus, which is a graphical depiction of the values the measures of performances of a system can take, when all the possible operating points are considered. This locus represents, therefore, the system capabilities. The concept can be generalized when instead of performance and workload, any measures of performance (MOPs) are considered. The locus then becomes the system locus. Similarly, the design requirements can be expressed in the performance space. In the case of organizations, performance as measured by accuracy and workload were the pertinent MOPs. Consequently, the corresponding requirements were for satisficing performance and for workload less than the bounded rationality constraint. In the case of C^3 systems, the requirements define another locus, the requirements locus L_r.

Measures of effectiveness (MOEs) are then quantities obtained by determining how well a system satisfies the requirements. In the case of organizations, the consistency measure Q was used as an MOE.

To illustrate the methodology, a generic version of the C^3 system for surface-to-air missile batteries was used. One novel aspect of the research was the modeling and analysis of timeliness as it pertains to C^3 systems.

5.3 PUBLICATIONS

The research results have been documented in full in thesis reports and technical papers. The pertinent publications are listed below:

Bejjani, G. J., (1985). Information storage and access in decision making organizations. M.S. Thesis, LIDS-TH-1434, Laboratory for Information and Decision Systems, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Bejjani, G. J., and Levis, A. H. (1985). Information storage and access in decision making organizations. Proceedings Eighth MIT/ONR Workshop on C3 Systems. Cambridge, Massachusetts.

Cothier, P.H. (1984). Assessment of timeliness in command and control. M.S. Thesis, LIDS-TH-1391, Laboratory for Information and Decision Systems, Massachusetts Institute of Technology, Cambridge, Massachusetts.

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Tomovic, M.M., and Levis, A. H. (1984). On the design of organizational structures for command and control. Proceedings Seventh MIT/ONR Workshop on C3 Systems. Cambridge, Massachusetts.

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Levis, A. H. (1984). Information processing and decision making organizations: A mathematical description. Journal of Large Scale Systems, No. 7.

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